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THE MODERN REFLECTING TELESCOPE AND THE NEW ASTRONOMICAL PHOTOGRAPHY

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INTRODUCTION

1. Several inventions which have been developed and demonstrated since 1910 solve some of the most serious difficulties encountered in the construction of great reflecting telescopes and in their use in astronomical photography. The present paper describes five of these inventions: (1) cellular discs for optical mirrors; (2) the Schwarzschild and the Ritchey-Chrétien "aplanatic" combinations of mirrors; (3) the extremely compact, economical mounting and dome which are possible for the equatorial Ritchey-Chrétien telescope; (4) the Fixed Universal telescope, with coelostat; and (5) the horizontal, electrical guiding mechanism for photographing with the Universal telescope.

2. Experience with solid glass discs of 102 inches diameter and 13 inches thickness, weighing more than 4·5 tons, proves that the casting and annealing of homogeneous discs of this size present difficulties which are practically insoluble even by the Saint Gobain Glass Company, the makers of most of the large reflector discs now in use. Serious defects of two kinds are encountered: (*a*) very large waves or surfaces of millions of small bubbles are present in the interiors, due to difficulties of pouring; (*b*) the necessity of very long annealing causes partial *devitrification* of the glass, which results in great loss of strength and rigidity of the disc. Obviously, nothing is gained by the great thickness formerly considered necessary. A solid disc 102 inches in diameter and 7 or 8 inches thick would be incomparably more easily and better annealed, and would be more rigid, than one of 13 inches thickness.

The 101-inch mirror of the Hooker reflector, Mt Wilson Observatory, is shown in Fig. 1 hanging on edge on its polishing machine in the Hooker Optical Laboratory. The photograph shows the innumerable bubbles in the interior of the disc.

The polishing machine is so designed that the mirror can quickly be turned from the *horizontal* position, in which it lies while being ground, polished, and figured, to the *vertical* position here shown, in which it hangs while being tested optically. This is done without removing the mirror from its cushioned turntable. The full-size polishing-tool or plate is shown, hanging on edge on its trunnions, on the right-hand side of the picture. The optical work on the mirror and its accessory mirrors, which included making an optically *plane* mirror 60 inches in diameter for the optical tests in the laboratory, required the greater part of the time and intensive care of myself and two assistants for five years.

3. Thick, solid glass discs, even when highly homogeneous, are subject to injurious changes of optical figure when in use at night, due to temperature changes. These changes of figure vary with the thickness of the disc and, of course, with the composition of the glass used. They become of serious moment in the case of large, solid, thick mirrors of ordinary glass.

4. In my opinion metallic mirrors made of cast metal alloys such as speculum-metal and "stellite" cannot properly be regarded as *optical* mirrors in the strict, modern sense of that term. Optically polished surfaces of these alloys, when examined with even a low-power microscope, show a granular or crystalline structure, and even castings of moderate size invariably have porous areas which are extremely troublesome in optical work.

5. On the other hand, however, optically polished surfaces of vitreous materials such as glass, pyrex, and fused quartz have a liquid-like quality; their structure is so fine that it cannot be detected even with the highest-power microscopes. When silvered by either the chemical or the cathode method, the silver film, deposited molecule by molecule on the polished vitreous surface, is so fine in structure that it takes the liquid-like quality of that surface. Further, the silver film is so thin, about 0·000004 inch, that it retains perfectly the optical figure (form) of the vitreous surface. Still further, its structure is so fine and dense that it is nearly opaque to the brightest light. These qualities, taken together, account for the very high reflective power of silvered vitreous surfaces when kept in fine condition. They account also for the fact that optically good mirrors with these surfaces permit the use of the full theoretical magnifying powers due to their apertures; these surfaces can therefore be regarded as *real optical* surfaces.

CELLULAR DISCS FOR OPTICAL MIRRORS

6. Cellular discs for optical mirrors are constructed from comparatively thin, highly-rigid plates of vitreous material, which retain their great strength and rigidity because they can be quickly and easily annealed. These discs consist of circular front and back plates, separated by a thoroughly ventilated rib-system built up of plates. All plates in the structure are selected for uniform thickness, uniform coefficient of expansion, uniform flexure-index, and freedom from marked striae and bubbles*.

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* G. W. Ritchey, *Compt. Rend.* **181** 1925 (208); *L'Astronomie,* **40** février, 1926 (57).

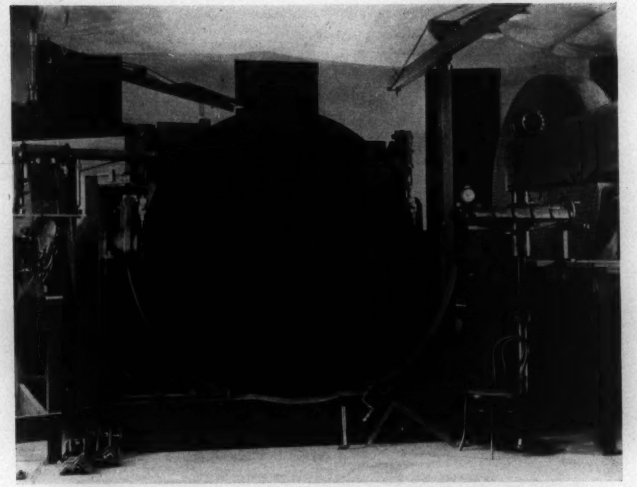

Fig. 1. The 101-inch mirror of the Hooker reflector, Mt Wilson Observatory.

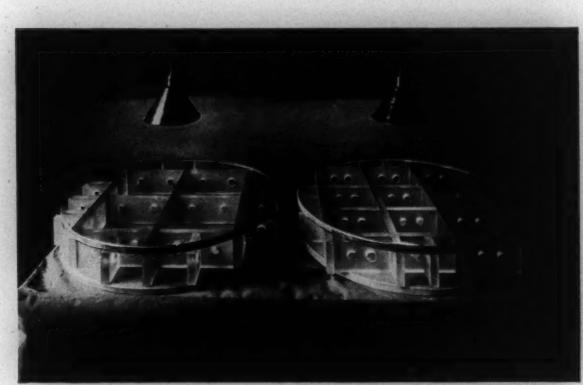

Fig. 2. Two 30-inch cellular plane mirrors

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Fig. 2 shows two 30-inch cellular plane mirrors which were made to determine the best distance apart of the ribs when glass plates one inch thick are used throughout. The interior rib-system of a 60-inch cellular mirror is shown in Fig. 3. This was made of unusually thin glass plates, six-tenths of an inch thick, in order that it might serve as a model, constructed to scale, for cellular mirrors ten or twelve feet in diameter. The depth of the rib-system is 8 inches.

7. Cellular mirrors have the following advantages:

(*a*) They retain the very high optical qualities of optically polished, silvered vitreous surfaces.

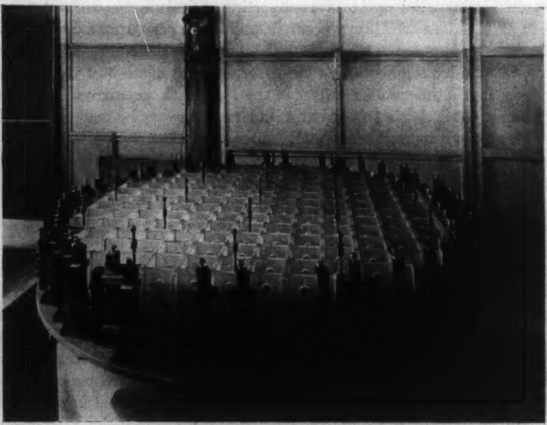

Fig. 3. Interior rib-system of a 60-inch cellular mirror

(*b*) They are light, weighing about one-fourth as much as solid mirrors of the same material and dimensions.

(*c*) Cellular mirrors having positive (forced) ventilation do not suffer changes of optical figure from such temperature changes as usually occur in the open dome at night. Optically plane mirrors *remain plane*, thus making possible for the first time great coelostats and great *fixed* or stationary telescopes of the highest optical quality, with all the incomparable advantages which this type affords for astronomical photography and for astrophysical work.

(*d*) We are aiming at the utmost attainable limit of perfection as well as of size in the great modern telescopes which are being planned. For this reason, and because of the possible danger of breakage due to the moderate degree of heat necessary with the best cements used for joining the component parts of cellular mirrors, we welcome the great advantage that this construction permits the use of many comparatively small units of low-expansion glass, pyrex, or fused quartz, instead of the single large unit, prohibitively difficult to secure, which is required for a solid disc. The use of these low-expansion vitreous materials will certainly contribute to the accuracy of optical figure and to the permanence of focal length of great reflectors throughout the night.

(*e*) Cellular mirrors, however large, can be made as thick (deep) as desired, to ensure great rigidity of the disc as a whole; and this without adding to the difficulty of construction.

(*f*) Cellular mirrors are better adapted than are solid ones for the application of the mechanical flotation-system for supporting optical mirrors without perceptible flexure in all positions which can occur in use*. The pressure of the counterpoise levers for lateral support can now be applied directly at the centres of gravity of the interior and exterior segments of the mirror, instead of around the edge of the mirror as formerly; the great advantage of this for very large mirrors is self-evident. Equally important is the fact that great cellular mirrors can be mechanically floated face-down, precisely as well as face-up.

(*g*) The component parts, comparatively small and light, of very large cellular mirrors can be transported without difficulty to the observatory site, and there cemented together. The optical work will be done at the observatory site.

8. It is perhaps natural that scepticism has been encountered in regard to the *optical permanence* of cellular mirrors made of vitreous materials cemented together. It is possible that a part of this scepticism, which is largely due to astronomers who do not claim to be opticians, nor even technicians, will be removed when I state that better and better methods have been developed, nearly continuously for 17 years, for *fitting* the adjacent surfaces to be cemented; that the fitting of these surfaces is now done by methods as accurate as those developed for my finest optical work; that the layer of cement remaining between these surfaces after cementing is only a small fraction of a micron in thickness; that better and better cements and methods of applying them have been gradually developed; that properly cemented joints are invariably stronger, under breaking tests, than the vitreous material itself; and that cellular mirrors up to 20 inches diameter, made in 1911 and 1912, have been used as the finest optical test-planes, without perceptible change of figure, for 16 years.

NECESSITY OF NEW TYPES OF REFLECTING TELESCOPES

9. The questions of the type of mirror-combinations and of the design of mountings for the better and larger reflecting telescopes which are made possible by the cellular construction of mirrors are of much interest and importance. My experience in the design, construction, and long-continued use of the 60-inch Mt Wilson reflector showed the advantages of that type, but also showed the directions in which important improvements could be made†.

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* G. W. Ritchey, *Smithsonian Contributions, Washington*, **34** 1904 (43).

† G. W. Ritchey, *Astrophys. Journ.* **29** April, 1909 (198).

10. A long study of the *refinements* which are possible in the use of great reflectors in astronomical photography shows the absolute necessity of improved *types* of reflecting telescopes, in order that these refinements may be used efficiently, and to the utmost limit of their possibilities. The use of these refinements is as indispensable for a great increase in accuracy of astronomical measurement as are more perfect and larger telescopes.

The Ritchey-Chrétien Type of Reflecting Telescope

11. In 1910, while I was engaged in astronomical photography with the 60-inch Mt Wilson reflector, M. Chrétien, of the Observatoire de Nice, visited Mt Wilson for several months for the purpose of studying the great reflector and its use. We then studied many improvements which had been suggested by my use of the 60-inch telescope in astronomical photography.

12. I was then also in charge of the design of the 101-inch Hooker reflector. I was facing the necessity of a dome 100 feet in diameter, and of a skeleton tube about 10 feet in diameter and about 50 feet long, if the general type of the 60-inch reflector were adopted for the 101-inch reflector.

13. I had already experienced for a year the inconvenience of photographing at the Newtonian focus of the 60-inch reflector—of following the large movement of the upper end of the tube while making the innumerable, quick, small corrections with the double-slide plate-carrier, which are necessary to secure the sharpest possible photographs*.

14. I had seen how sensitive is a great, highly refined equatorial reflector to slight changes of temperature†. I had also seen the necessity of quick interchange of the tube-extensions which carry the various secondary mirrors. To make this interchange at night with safety, and quickly enough to take the fullest possible advantage of changing conditions with respect to atmospheric definition and to moonlight, requires, for large reflectors, special and very carefully designed mechanism.

15. I had seen for a year how small is the measurable field of a short-focus paraboloidal mirror of large aperture and good figure, on account of the coma or aberration of the out-of-axis images. In my early work at the Newtonian focus of the 60-inch Mt Wilson reflector the field used was approximately 70 × 90 minutes. It was soon evident that this field was much larger than was generally useful, the star-images toward the edges of the field having a very strongly marked arrow-head form. Only for the discovery of large numbers of small, faint nebulae was it desirable to use so large a field. A new double-slide plate-carrier was designed and constructed, with many improvements which had been suggested by my early use of this telescope.

16. The field of the new plate-carrier is only 38 minutes (84 mm.) square; this includes all the field which is generally useful at the Newtonian focus of the 60-inch

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* A. A. Common, *Monthly Notices R.A.S.* **49** 1888–9 (297).

† G. W. Ritchey, *Astrophys. Journ.* **32** July, 1910 (283).

reflector. For purposes of very exact measurement only, a circular field 15 minutes (33 mm.) in diameter would be the maximum which could be used to advantage; and near the edge of even this field the star-images are not as small, intense, and symmetrical in form as they should be for most accurate measurement, because of the aberration of all out-of-axis images at the Newtonian focus.

17. The great importance of the last-named difficulty, and of all the others just mentioned, becomes so marked in very large and refined instruments that I had made an intensive study with the object of finding methods by which these difficulties could be decreased or eliminated in the 101-inch reflector. It was certain that all of these difficulties would be accentuated in the larger instrument if it were constructed on a similar plan.

18. Could we expect to find, by any possible good fortune, a type of reflector in which all of the difficulties just described would be eliminated or greatly decreased? It was in the endeavour to do this that I investigated, with M. Chrétien, the possibilities of a very short, modified Cassegrainian type, with new curves of the mirror surfaces, in which the ratio of equivalent focal length to aperture would be between 6 and 7 to 1, that is, small enough to permit the photography of very faint nebulae. It was evident that a Cassegrainian type in which the focal ratio of the large mirror would be 4 to 1, and in which the magnification given by the small convex mirror would be 1·6 or 1·7 times, would give the desired equivalent focal ratio of 6·4 or 6·8 to 1, and at the same time would give a very compact, light, rigid, and economical type of mounting, requiring only a small and economical dome and building. The motion of the observer in following the focus, which would now be near the centre of motion of the telescope, would always be small and slow, thus ensuring his convenience and safety, and greatly increasing his ability for rapid and skilful work. The shortness of the tube would make practicable refinements which would enormously decrease its flexures and the effects of temperature changes, thus conserving the alignment and mutual adjustment of the two mirrors.

19. It was shown by mathematical investigation that if we would confine ourselves, for the finest possible results, to a single equivalent focal ratio in a given telescope, by using always *in combination* a single pair of mirrors, large concave and small convex, with curves slightly different from the paraboloid and hyperboloid, respectively, of the Cassegrainian, it would be possible to improve very greatly the field and the smallness, light-concentration, and symmetry of form of the out-of-axis images of the short-focus reflector. The new combination of curves is especially chosen to eliminate entirely the coma of the out-of-axis images, while at the same time retaining the perfect central image. The most perfect field of extremely small images given by this combination is a slightly curved one, concave toward the incident light; so that to realise the fullest possible advantage of this type we must use slightly concave, spherical, photographic plates, or a correcting lens nearly in contact with flat photographic plates*.

20. It is important to note that greater equivalent focal lengths can easily be

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* H. Chrétien, *Rev. d'Opt.* **1** 1922 (1–28); G. W. Ritchey and H. Chrétien, *Compt. Rend.* **185** 1927 (266); G. W. Ritchey, *loc. cit.* **185** 1927 (640).

secured with the same instrument, for spectrographic work and for direct photography with high powers, by substituting a second, and, if we wish, a third, small convex mirror in the place of the principal one. This is done by means of interchangeable tube-extensions, each of which carries its own secondary mirror. These second and third convex mirrors do not give so large a field as the principal one gives, because only one form of small convex mirror can be rigorously fitted to, or matched with, a given large concave mirror, to secure the condition of entire freedom from coma of the out-of-axis images; but the second and third small convex mirrors do give practically perfect images at and near the centre of the field*.

The Schwarzschild Type of Reflecting Telescope

21. While investigating the character of the curves of the two-mirror combination required to secure the conditions described above, we availed ourselves of the remarkable memoir of Schwarzschild entitled *Theorie der Spiegeltelescope*†. Schwarzschild considers the case of a two-mirror reflector having a large concave and a small concave mirror used always in combination. His fine mathematical treatment of the problem is of a perfectly general character; his formulae, with the necessary changes of sign, are applicable in the case of the short, new-curve Cassegrainian type in which we are especially interested, for reasons given more fully below.

22. Schwarzschild in his type places the small concave mirror inside the focus of the principal mirror, and modifies the curves of both to secure the conditions of freedom from coma of the out-of-axis images and, at the same time, a perfect central image. He thus secures a large (angular) field of very small, round images, together with a remarkably small ratio of focal length to aperture—as small as 3 to 1 or even 2·5 to 1, if desired.

23. Schwarzschild said to me in 1910 that he regarded this telescope as a special type for a special purpose—a very small focal ratio with large field—and that he did not consider it of general usefulness, because of its many practical difficulties. The considerable length of the telescope tube as compared with that of other modern reflector types; the large size of the secondary concave mirror which, in the form illustrated by Schwarzschild in his memoir, has about one-half the diameter of the principal mirror; the considerable percentage of light obstructed by this secondary mirror; the fact that the photographic plate must be *in the axis* and between the two mirrors, thus obstructing to some extent the cone of light reflected from the principal mirror; the inaccessibility of the photographic plate-carrier for purposes of centering, focusing and selecting of guide-stars, also for guiding, refocusing and correcting for rotation of field during long exposures; the difficulty of maintaining the necessary mutual alignment of the two mirrors, because of the flexures of the tube due to its length and to the weight of the relatively large secondary mirror and its cell; all these difficulties are strongly opposed to economy of construction and to efficiency and convenience in use. Some of these difficulties,

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* H. Chrétien, *Compt. Rend.* Nov. 21, 1927.

† K. Schwarzschild, *Theorie der Spiegeltelescope*, Potsdam, 1905.

however, disappear, while most of the others can be very much diminished, when this telescope is constructed on a large scale and is used as a fixed telescope with coelostat*.

24. So far as the writer knows, Schwarzschild's type of telescope has never been completely demonstrated in use. It is one of the most important developments which should be fully demonstrated on a fairly large scale in an astronomical laboratory, for it will prove of revolutionary importance in photographing extremely faint stars and nebulosities with fine definition over a large field.

25. It is unaccountable that, so far as his memoir indicates, Schwarzschild did not consider the importance of the application of the general principles demonstrated in his memoir to the very short, modified Cassegrainian type. This second large-field, two-mirror type is the *Ritchey-Chrétien*. It differs from the Schwarzschild type in the following fundamental characteristics: (*a*) It is adapted, not for one special purpose only, but for the broadest general usefulness in astronomical photography. (*b*) Its arrangement of mirrors is such as to give a most convenient form of telescope, the focus of the optical combination being in an accessible position, near the centre of motion of the telescope, and never far above the floor of the dome. (*c*) The telescope tube is very short, and is therefore well adapted for the economical use of improvements which decrease its flexures and its expansion and contraction at least a hundred times, thus ensuring a corresponding degree of permanence of alignment and of separation of the two mirrors. (*d*) The principal equivalent focal

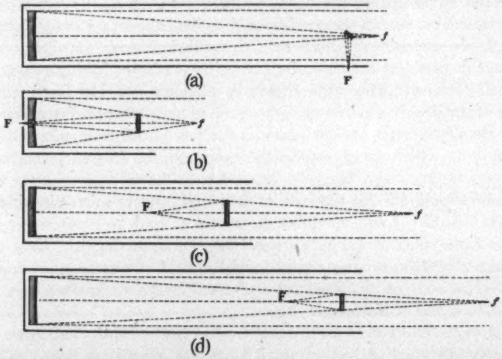

Fig. 4. Diagrams showing paths of light-rays, and also relative lengths, of various types of reflectors
(*a*) Newtonian reflector (focal ratio 6·8 : 1)
(*b*) Ritchey-Chrétien reflector (focal ratio 6·8 : 1)
(*c*) Schwarzschild reflector of form which gives nearly flat field (focal ratio 3·0 : 1)
(*d*) Schwarzschild reflector of form which gives best out-of-axis images, but slightly convex field (focal ratio 3·0 : 1)

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* G. W. Ritchey, *Compt. Rend.* **185** 1927 (758).

ratio can be chosen as the best one for general photographic work, for example, a focal ratio of 6·4 or 6·8 to 1; for this we use the rigorous combination of new curves which give a maximum field of very small images without coma. Without changing the large mirror, greater equivalent focal ratios are secured efficiently and economically whenever desired, as explained above. (*e*) The small secondary mirrors are but little larger, in comparison with the principal mirror, than those of the ordinary Cassegrainian type. (*f*) There is no obstruction in the cone of light reflected from the large mirror. (*g*) The entire telescope is very compact in form, and is therefore well adapted for the complete protection of all parts of it from the large changes of temperature between day and night. (*h*) It permits the use of a dome and its supporting building both of which are exceptionally small and economical.

26. The four diagrams in Fig. 4 show the paths of the light-rays and the relative lengths of the Newtonian, Ritchey-Chrétien, and Schwarzschild telescopes. Fig. 4 (*a*) shows a Newtonian reflector having a focal ratio of 6·8 to 1. Fig. 4 (*b*) shows a Ritchey-Chrétien reflector having the same "equivalent" focal ratio, the same effective focal length. Fig. 4 (*c*) shows a Schwarzschild system having an "equivalent" focal ratio of 3 to 1; this is the form illustrated by Schwarzschild in his paper, in which the diameter of the secondary mirror is one-half that of the large mirror. Schwarzschild chose this form because the field is nearly flat and the tube is comparatively short. Fig. 4 (*d*) illustrates the Schwarzschild form (shown with the same focal ratio, 3 to 1) which gives the most perfect images over a very large, slightly convex field. The necessary condition in this form is that the distance between the two mirrors shall be equal to twice the equivalent focal length. In the writer's opinion this is incomparably the most important form of the Schwarzschild type.

A COMPARISON, IN THE LABORATORY, OF THE STAR-IMAGES AND FIELDS OF THE NEWTONIAN AND RITCHEY-CHRÉTIEN REFLECTORS

27. In the optical laboratory of the Paris Observatory I made the mirrors of a Newtonian reflector and also those of an aplanatic reflector of the Ritchey-Chrétien type. Each of these has an aperture of 19·9 inches and a focal length of 136 inches*. My purpose was to compare rigorously the star-images and fields of the two types of telescope, and to do this in the laboratory, where nearly perfect conditions of quiet air and constant temperature could be maintained.

28. After the optical surfaces were completed and silvered, each system of mirrors, in succession, was set up on an all-metal optical bench, in combination with an optically plane, silvered mirror of 30 inches diameter. The similar use of a large plane mirror in the optical testing of Newtonian and Cassegrainian reflectors has been fully described by me†. The 30-inch plane mirror used in making this comparison is of the built-up, cellular construction, and has retained its optical figure

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* This focal length is approximately that of the photographic refractors used for the *Carte du Ciel*.

† G. W. Ritchey, *Astrophys. Journ.* **19** 1904 (53); *Smithsonian Contributions*, **34** 1904.

for three years without change which can be detected by the most sensitive optical tests.

29. The artificial star used in this comparison is approximately one micron in diameter, and is produced by the use of a tungsten-arc lamp, a small needle-hole, and a microscope objective. In each telescope the artificial star remains always fixed, at the focus, in the axis. If the telescope mirrors are in good alignment, and if the large plane mirror is at right angles to the axis of the telescope, the light from the artificial star, after reflection by the telescope mirrors, then by the large plane mirror, and again by the telescope mirrors in reverse order, forms a reflected image or focus precisely at the position of the artificial star. If now the large plane mirror be rotated slightly about a vertical axis, the reflected image is formed at one side of the artificial star and of the axis. The arrangement of parts is such that the reflected images can be examined in all positions between the limits 2·5 and 60 minutes from the axis.

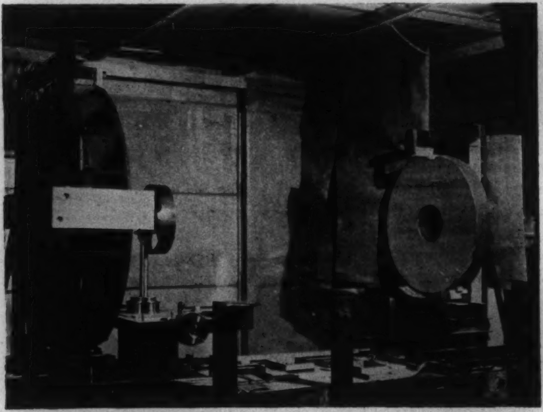

Fig. 5. Ritchey-Chrétien mirrors set up on an all-metal optical bench in combination with a 30-inch optically plane mirror, for studying the out-of-axis images

30. The reflected images are examined by means of a microscope magnifying about 100 diameters, and having a micrometer-eyepiece. This microscope can be clamped in any position between 2·5 and 60 minutes from the axis of each telescope; its focal setting (in the direction parallel to its own axis) is determined by means of a micrometer, reading to 0·01 mm., and by a Brown and Sharpe straight-edge of the finest quality. The microscope thus serves for studying and measuring the out-of-axis images, and also for determining the curvature of the field of best images, of each telescope.

31. In Fig. 5 we see the 19·9-inch Ritchey-Chrétien concave mirror at the right, the cell containing the convex mirror of 7·2 inches diameter at the left, and the 30-inch cellular plane mirror at the extreme left. The distance between the vertices of the two curved mirrors is 41·75 inches. The microscope is not shown, as it is behind the concave mirror.

32. In examining with the microscope the images formed at different distances from the axis, I have in each case chosen and recorded the focal setting at which the largest percentage of the total light of each image is concentrated in the smallest area. This practical and rigorous procedure differs from theoretical investigations of such images in that it necessarily takes full account of the distribution of light in the images, due to the combined effects of aberration and diffraction. The images thus selected I shall call images of *maximum concentration*.

Images and Field of the Newtonian Reflector

33. The out-of-axis images have the familiar arrow-head form, that is, with coma, the point or vertex of the arrow-head being always toward the centre of the field. The size of these images is, in general, directly proportional to their distance from the axis. But their form, and the distribution of light in them, changes markedly with small changes of focus.

34. In the flat Newtonian field used in astronomical photography at present a large percentage of the light of each image, at all distances from 5 to 60 minutes from the axis, is distributed fairly uniformly over approximately one-half of its length which is adjacent to its vertex; one-fourth or more of the light of each image is in the two strong, curved rays which form its boundaries; there is no marked concentration of light at its vertex. Unfortunately, the fraction "approximately one-half" just used is not constant, but varies with the brightness of the star, becoming larger for bright stars, and vice versa. This and other properties of the Newtonian images are prohibitive for very high accuracy of measurement of photographs (see Fig. 6).

35. If we move the eyepiece gradually forward, we see that the angle of the vertex increases, the two side rays become fainter and more nearly straight, and the light of the image becomes more and more concentrated at and near its vertex, until we reach the focus of maximum concentration. The field or locus of the images of maximum concentration is, unfortunately, not a plane nor a spherical surface, but is an approximate hyperboloid, concave toward the incident light. If we compare the out-of-axis images of this best curved field with the corresponding ones in the flat field exclusively used at present, we find that the gain in concentration of light in favour of the former is about fourfold, the area of concentration being approximately one-fourth. This proportion holds, very approximately, for images at all distances between 5 and 60 minutes from the axis. Fig. 6 shows the comparison of the images at various distances from the axis, the left-hand and the central vertical columns showing the appearance of the images in the flat and in the concave Newtonian fields respectively. The angular dimensions of the images are indicated by the scale below.

Images and Field of the Ritchey-Chrétien Reflector

36. I describe herewith the images observed in the optical tests of the new-type telescope of 19·9 inches clear aperture and 136 inches focal length. The large concave mirror has a focal ratio of 3·25 to 1; the small convex mirror magnifies 2·1 times; the equivalent focal ratio is therefore 6·825 to 1. The focus F is at a point 6·3 inches back of the vertex of the optical surface of the large mirror; the distance between the vertices of the optical surfaces of the two mirrors is 41·73 inches; the diameter of the central hole in the large mirror, to allow for field and for exterior guide-stars, is 4·9 inches; the clear aperture of the small convex mirror is 7·1 inches.

The field or locus of the images of maximum concentration is spherical, concave toward the incident light; its radius of curvature is 23·62 inches. In this curved field each of the images at distances 2·5, 5·0, 7·5, and 10·0 minutes from the axis appears as a normal, brilliant diffraction disc of diameter 0·28 second, surrounded by normal diffraction rings. What is most remarkable is that each of the images at distances 12·5, 15·0, 17·5, and 20·0 minutes from the axis still appears as a brilliant diffraction disc of diameter about 0·28 second, surrounded by its rings. But in these latter images the diffraction rings become slightly and progressively brighter; this is unquestionably due to the presence of the aberration-pattern, very small and symmetrical in form, which at the distance of 20 minutes from the axis is 0·9 second in diameter. It is not until we reach the distance 22·5 minutes from the axis that the appearance of the images is distinctly changed by the aberration-pattern. At greater distances from the axis the form and size of the images are determined more and more by the aberration-pattern. In the best curved field this form is always approximately circular; the illumination of the images is approximately symmetrical both radially and tangentially with respect to the centre of the field; the diameters of the aberration-images vary as the square of their distances from the axis; and at the distances 30, 45, and 60 minutes from the axis these diameters are 2·0, 4·5, and 8·0 seconds respectively.

37. In Fig. 6 the left-hand vertical column shows the appearance of the Newtonian images in the flat field almost exclusively used in astronomical photography at present, at distances of 2·5, 5·0, 10·0, 15·0, and 20·0 minutes from the axis; the central vertical column shows the corresponding Newtonian images in the best concave (hyperboloidal) field; the right-hand column shows the corresponding Ritchey-Chrétien images in the best concave (spherical) field.

38. It seems superfluous to state that, even with the types of photographic telescopes in use at present, a great gain can be made by using photographic plates the glass surfaces of which have been ground and polished approximately flat or, far better, to the curvature of the best field*. When the observer becomes expert in the use of the knife-edge focusing device used with the 60-inch Mt Wilson reflector, the focal plane of the image of a star in the axis of that telescope can quickly be

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* In the case of the photographic plates used for the *Carte du Ciel*, all those which were used in France, and those which were supplied by France for foreign observatories, had the sensitive emulsion coated on thin, square sheets of ground and polished plate-glass.

determined to within 0·001 inch*. The irregularities of surface of commercial photographic plates almost exclusively used in astronomical photography at present are from 5 to 30 times greater than the amount just named, depending, in part, upon the size of plates used; the results are loss of sharpness of details photographed, loss in accuracy of measurement of the photographs, and the total loss of hundreds or thousands of the faintest star-images which would otherwise be recorded in long-exposure photographs.

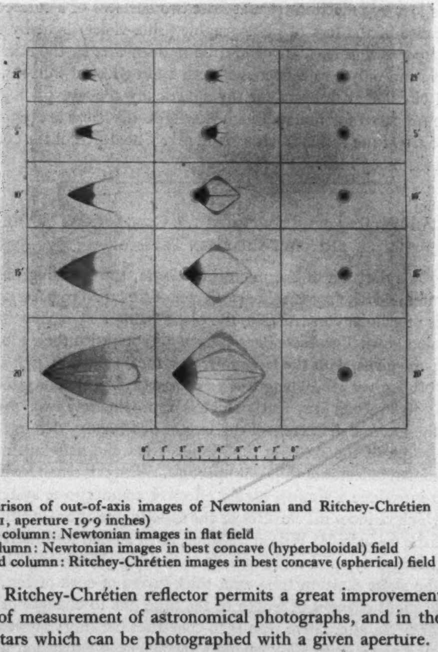

Fig. 6. Comparison of out-of-axis images of Newtonian and Ritchey-Chrétien reflectors (focal ratio 6·8 : 1, aperture 19·9 inches)
Left-hand column: Newtonian images in flat field
Middle column: Newtonian images in best concave (hyperboloidal) field
Right-hand column: Ritchey-Chrétien images in best concave (spherical) field

39. The Ritchey-Chrétien reflector permits a great improvement to be made in accuracy of measurement of astronomical photographs, and in the faintness of out-of-axis stars which can be photographed with a given aperture. But in order to utilise to the fullest possible degree these advantages, which are due chiefly to the very small, symmetrical star-images given by this telescope, we must use the necessary refinements both of photographic plates and of the mechanical parts and accessories of the telescope.

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* G. W. Ritchey, *Astrophys. Journ.* 32 1910 (287); see Table.

Photographic Plates for the Ritchey-Chrétien Reflector

40. Leaving aside for the present the subject of special photographic emulsions for astronomical photography, it is clear that we must use either photographic plates the glass surfaces of which are ground and polished flat, in combination with a correcting lens for rendering the field flat; or, on the other hand, photographic plates the glass surfaces of which are ground and polished to a spherical surface of the proper radius of curvature. The writer prefers the latter method because of the light which is lost by reflection from at least two surfaces of a correcting lens, and far more because of the loss of photographic (blue-violet) light by absorption in even the best correcting lens. It should be noticed that in the Ritchey-Chrétien telescope there are only two reflections, both from silvered mirrors. The ground and polished circular glass bases for the spherically concave photographic plates which I have prepared for the 19·9-inch new-type telescope are 3·5 inches (about 90 minutes of arc at the focus) in clear diameter. The depth of the concave surface of these plates is 0·065 inch.

ADVANTAGES RESULTING FROM THE COMPACTNESS OF THE RITCHEY-CHRÉTIEN TELESCOPE

41. Fig. 7 is a diagram of the mounting, dome, and building required for an equatorially mounted Ritchey-Chrétien reflector of 6 metres (19·7 feet) aperture. The large mirror is of cellular construction, the plates being 1·25 inches thick and made of low-expansion glass. Two secondary convex mirrors, with their tube-extensions, are provided; one gives, with the large mirror, a focal length of 40·8 metres (about 135 feet); the other gives a focal length of 72 metres (236 feet). The internal diameter of the dome is 38·8 metres (127 feet), which is approximately twenty-five per cent. greater than the internal diameters of the largest observatory domes now in use.

42. The length of the skeleton tube is less than one-half that required for a modern Newtonian reflector of the same aperture. With this small length it becomes practicable to introduce a simple, highly effective counterpoise system of four or eight levers which reduces the flexures of the tube to one-thousandth part of those of the tube of the 60-inch Mt Wilson reflector, itself an extraordinarily rigid one of the older and longer type. In addition, it is entirely practicable to cover all the members of the short skeleton tube with thick layers of cork or felt, thus greatly decreasing the slight changes of length of the tube due to changes of temperature during the night. An alternative plan is to construct the short skeleton part of the tube entirely of a nickel-steel alloy having a coefficient of expansion which is practically zero, in other words, an approximate "invar."

43. The telescope mounting and tube are so compact that it becomes practicable to enclose the massive parts of the mounting, the mirrors, and the entire tube in a constant-temperature chamber within the dome, during the day, thus holding the entire telescope at the expected night temperature. The ceiling and walls of this cylindrical chamber are of soft, thick felt, quilted between covers of strong canvas.

A very small refrigerating plant inside the chamber holds the entire interior at the expected night temperature throughout the day. When not in use the chamber is raised by suitable mechanism, is closed like an umbrella, and is drawn closely against the interior surface of the dome.

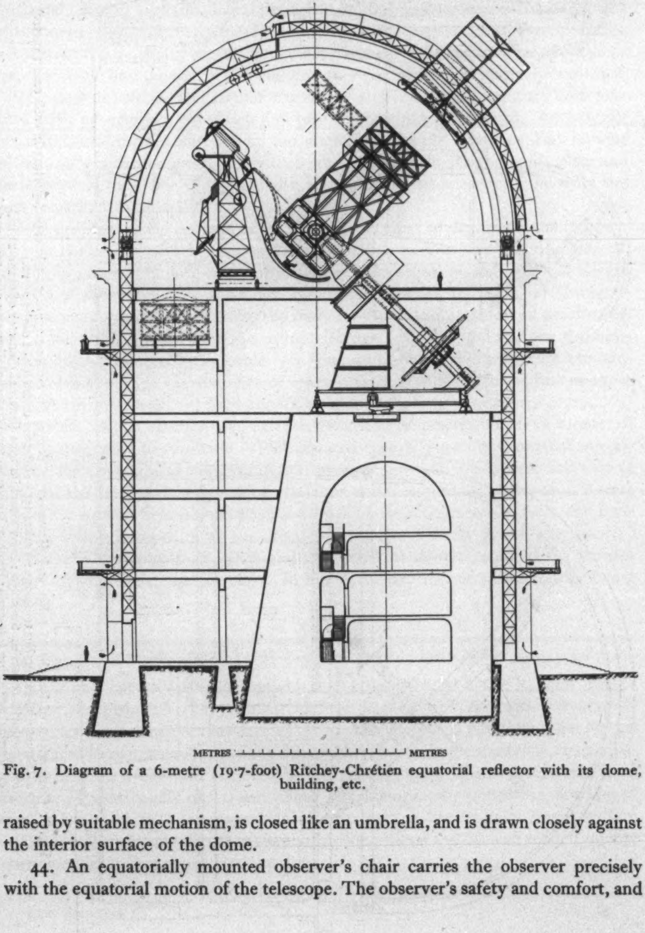

Fig. 7. Diagram of a 6-metre (19·7-foot) Ritchey-Chrétien equatorial reflector with its dome, building, etc.

44. An equatorially mounted observer's chair carries the observer precisely with the equatorial motion of the telescope. The observer's safety and comfort, and

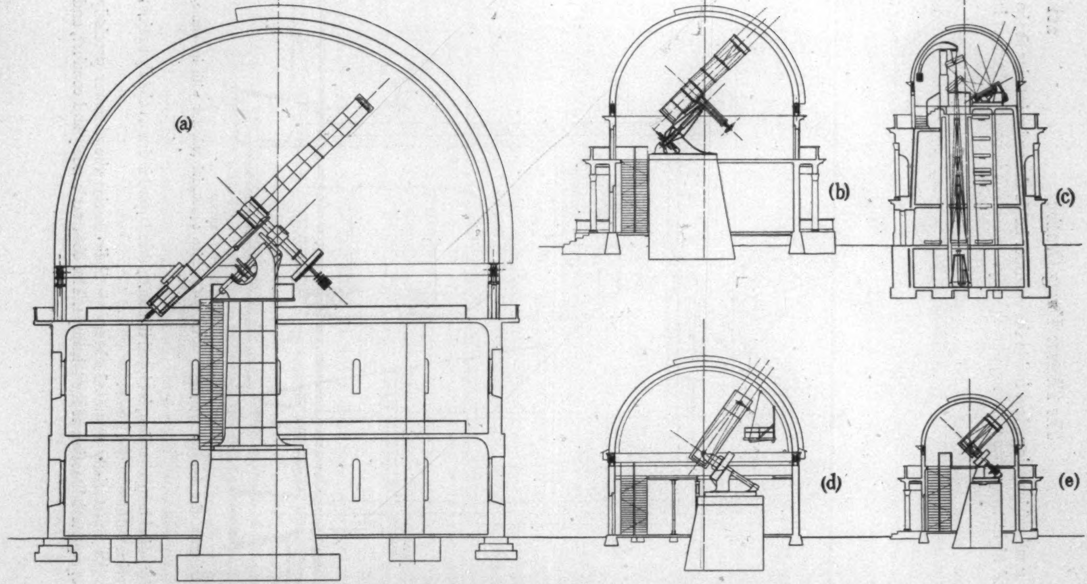

Fig. 8. Comparison of lengths of tubes and diameters of domes for various types of telescope (aperture in each case 1 metre)
(*a*) Equatorial refracting telescope: Yerkes type (internal diameter of dome 26 m.)
(*b*) Equatorial reflecting telescope: Schwarzschild type (internal diameter of dome 11 m.)
(*c*) Vertical reflecting telescope: Ritchey Universal type (internal diameter of dome 6·5 m.)
(*d*) Equatorial reflecting telescope: Mt Wilson type (internal diameter of dome 11 m.)
(*e*) Equatorial reflecting telescope: Ritchey-Chrétien type (internal diameter of dome 5·5 m.)

his ability for rapid and skilful work in guiding and in every kind of observing is thus very greatly increased.

The weight and the cost of the dome required for the compact Ritchey-Chrétien equatorial reflector are each about one-eighth as great as those of the dome required for a modern Newtonian reflector of the same aperture. In the case of the supporting cylindrical steel building the diameter, not the height, is reduced to one-half or less; the weight and the cost of this building are reduced to approximately one-third.

45. As indicated in the diagram, the all-metal dome and building are both provided with an exterior, ventilated sun-protection which I invented. An exterior tube-extension, carried entirely by the dome, not by the telescope, but moving *automatically* with the latter, is provided; this protects the photographic plate and the interior of the dome from sky-light, and protects the telescope from wind and from radiation to the night sky.

It is perhaps well to summarise very briefly the chief advantages of the Ritchey-Chrétien compact equatorial type as compared with a modern Newtonian equatorial: (*a*) The length, weight, and cost of the tube are reduced to one-half. (*b*) The weight and cost of the entire telescope mounting are substantially reduced. (*c*) Temperature-protection of the tube during the night (while in use) is rendered practicable. (*d*) Temperature-protection of the entire telescope, including the mirrors, throughout the day, is rendered practicable. (*e*) Flexures of the tube are decreased to one-thousandth part. (*f*) Convenience of quick interchange of mirror-combinations is substantially increased. (*g*) An equatorially-mounted observer's carriage is rendered practicable. (*h*) An exterior tube-extension is rendered practicable. (*i*) Diameter of dome is decreased to one-half. (*j*) Weight and cost of dome are decreased to one-eighth. (*k*) Diameter of building is decreased to one-half. (*l*) Weight and cost of building are decreased to one-third. (*m*) The surface-intensity of out-of-axis star-images for needed fields is increased sixteen-fold. (*n*) Symmetry of form and consequent ability to measure all out-of-axis star-images are very greatly increased.

The relative lengths of tubes and diameters of domes required for various modern types of telescope are shown in Fig. 8, the aperture of each telescope being 1 metre.

THE FIXED, VERTICAL, UNIVERSAL TELESCOPE*

46. Long experience in astronomical photography with the 24-inch Yerkes reflector, the 40-inch Yerkes refractor, and the 60-inch Mt Wilson reflector, supplemented by much longer experience in my own astronomical laboratory, has shown the possibility of a large number of extreme refinements in the materials, the instruments, and the technique of astronomical photography. The cellular, ventilated mirrors, already briefly described, afford one example; by permitting the use of small selected units of low-expansion glass, pyrex, or fused quartz this invention makes possible optical mirrors of such great dimensions and of such refined quality as were never before considered possible.

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* G. W. Ritchey, *Compt. Rend.* **185** 1927 (758).

The Schwarzschild and Ritchey-Chrétien combinations of mirrors afford another example; for the angular fields required for every conceivable problem of astronomical photography, including the making of most accurate astronomical measurements, these combinations of mirrors give star-images which are practically diffraction discs over the entire fields. To take full advantage of such small, round, intense images we must have better types of telescope-mountings and better methods for their use.

47. The new photographic plates with accurately ground and polished surfaces which coincide rigorously with the curved telescopic fields, together with special photographic emulsions for astronomical photography, and the refinements and economies briefly mentioned in connexion with the 6-metre Ritchey-Chrétien equatorial reflector, afford additional examples. A number of others will be mentioned near the end of this paper. It has long been evident that the use of these refinements will contribute fully as much to the improvement of astronomical photography and to the accuracy of astronomical measurement as the construction of much greater telescopes, alone, would contribute. But it has become equally evident that in order to utilise these refinements to the utmost limit of their possibilities we must adopt a *fixed* or stationary type of telescope, with coelostat, with which all refinements and all accessory instruments can be used with the elaboration and the perfection of conditions possible in a fixed physical laboratory. This type of telescope is here briefly described.

48. Fig. 9 illustrates a fixed, vertical, universal telescope of the latest form planned by the author. In agreement with M. Delloye, Director-General of the Saint Gobain Glass Company, whose close and generous collaboration I have enjoyed in all matters relating to cellular mirrors, this plan is made for a universal telescope of 5 metres (16·4 feet) aperture, the plane mirrors of the coelostat being 6 metres (19·7 feet) in diameter. This "multiple unit" telescope includes only Schwarzschild and Ritchey-Chrétien combinations of mirrors. There are six 5-metre concave mirrors, two of which are Schwarzschild and four are Ritchey-Chrétien. There are nine smaller secondary mirrors, two of which are concave (Schwarzschild), and seven convex (Ritchey-Chrétien).

49. The two Schwarzschild combinations have focal ratios, respectively, of 2·75 and 4·0 to 1; the corresponding focal lengths are respectively 13·75 metres (45·1 feet) and 20 metres (65·6 feet).

50. The seven Ritchey-Chrétien combinations have focal ratios, respectively, of 6·8, 10·5, 16·0, 27·0, 40·0, 60·0, and 90·0 to 1; the corresponding focal lengths are respectively 34·0 metres (111·5 feet), 52·5 metres (172·2 feet), 80·0 metres (262·5 feet), 135·0 metres (442·9 feet), 200·0 metres (656·2 feet), 300·0 metres (984·3 feet), and 450·0 metres (1476·4 feet). It should be noted that four of these are rigorous "aplanatic" combinations, namely, the first, second, third, and fifth; the others are *approximate* aplanatic combinations (see paragraph 20).

We should note that each of the great focal lengths here named is secured by the combination of two optical mirrors, large concave and small convex, without the necessity of actual great length of the telescope itself. Thus, for the focal length

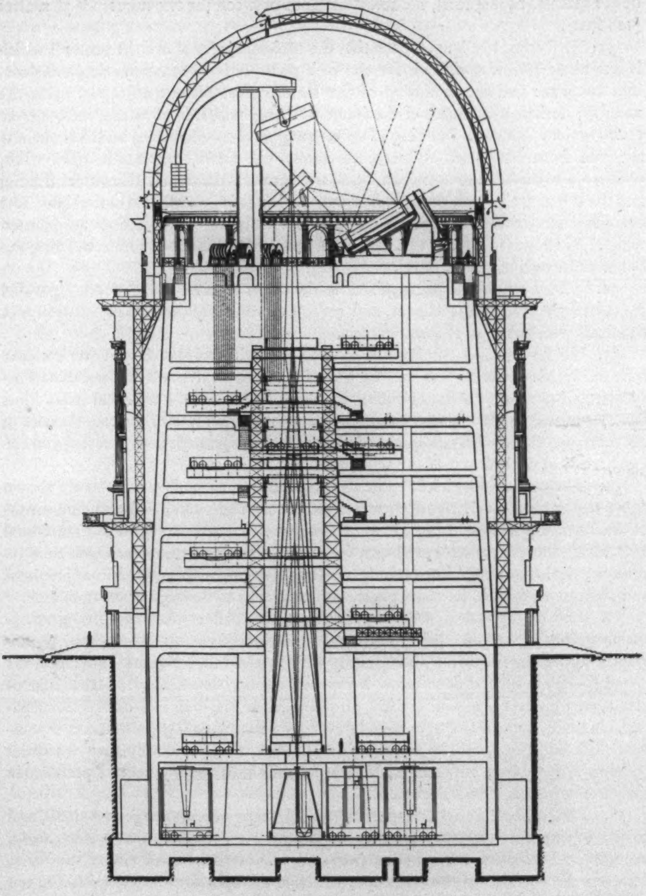

Fig. 9. Diagram of a 5-metre fixed vertical universal telescope with a 6-metre coelostat, showing arrangement of interior. The equipment includes six interchangeable large concave mirrors and nine smaller secondary mirrors

of 450 metres (1476·4 feet), the actual distance between the two mirrors is 36 metres (118 feet).

51. Referring to Fig. 9, we see that the coelostat is far above the ground, which is an indispensable condition for the best possible local atmospheric conditions. The coelostat and the mounting of the second great plane mirror rest upon the massive, horizontal summit of the inner building, which is of reinforced concrete construction. An outer building of very strong steel construction, which is entirely separate from the inner building, surrounds the latter, protects it from wind, weather, and rapid temperature changes, and supports the dome. The outer building and the dome are in turn protected by an exterior, light, sheet-steel sun-shield. The two sheet-steel walls are separated by ample ventilating space, and all are painted white. As shown in Fig. 9, two stories or floors of the inner concrete building are below the exterior ground-level.

52. The second large plane mirror in the dome receives the stationary, parallel beam of light from the coelostat, and reflects it vertically downward, centrally, in the fixed, vertical tube of the telescope.

53. On the first floor below the outside ground-level the six 5-metre concave mirrors lie horizontally, face up, each on its own complete mechanical flotation-system and carriage, the latter rolling smoothly on straight, horizontal rails. Thus any one of these mirrors, as desired, can be moved quickly into the exact centre of the telescope tube, with automatic adjustment and alignment with reference to the fixed, vertical optical axis of the telescope.

54. The carriages which support the nine smaller, secondary mirrors are shown above the ground-level. Six of these are seen at the right and left (north and south) of the vertical telescope tube. Three others move east and west; the six horizontal rails which support them are shown in section. Each of these carriages rolls on straight, horizontal rails into exactly central position, with automatic adjustment and alignment, each in its exact plane with reference to its large concave mirror.

55. The astrophysical accessory instruments—prism-spectrographs, grating-spectrographs, thermo-couples, radiometers, bolometers, interferometers, photographic apparatus for direct photography with low and high powers—are all on the lowest floor, the second floor below the outside ground-level. Each of these instruments, of whatever size, elaboration, and refinement desired, and each in its separate, enclosed, constant-temperature laboratory with insulating walls and with concrete floor and piers, can be rolled, without shock, more smoothly than the finest Pullman railway car, on straight, horizontal rails into exactly central position in complete adjustment and alignment.

56. The rolling carriages supporting the telescope mirrors, large and small, and those carrying the accessory instrument laboratories, are all moved electrically, smoothly, all of them horizontally, into and out of their exact central position. Whatever be the size of the telescope, whether the aperture be one metre or ten metres, the interchange from any one complete combination of mirrors and accessory instruments to any other combination, in complete adjustment and alignment, ready for instant use, can be accomplished in four minutes.

57. The square, vertical tube of the telescope consists, primarily, of four vertical, square columns at its four corners. These columns, above the third or ground floor, are of strong steel construction, and are separate from the concrete inner building. These steel columns are connected together by horizontal members of steel, and all these parts are heavily insulated with cork, so that expansion and contraction from temperature changes are very slow and small. The horizontal steel girders and rails on which roll the carriages of the secondary mirrors are supported entirely by these four vertical, insulated steel columns. At and below the ground-floor the four vertical columns are of concrete, and may be constructed, if desired, as a unit with the ground floor and the two floors below.

58. Some of the marked advantages of the fixed, universal type of reflecting telescope may be enumerated as follows:

(*a*) The convenience, comfort, and safety of the observers (and their consequent ability to do skilful and rapid work) are perfect; and equally so whatever be the size of the telescope, whether the aperture be one metre or ten metres.

(*b*) Every known refinement for visual, photographic, spectrographic, and physical-laboratory observations can be used under the most perfect laboratory conditions, and therefore to the utmost limit of its possibilities.

(*c*) Every known useful form of reflecting telescope—Newtonian; Cassegrainian combinations of different focal ratios; the large-field types with small, symmetrical images (Schwarzschild and Ritchey-Chrétien), of varying focal ratios—can be used, interchangeably, as desired.

(*d*) Accessory instruments—astrophysical apparatus of all kinds; photographic attachments for direct photography with low and high powers; the elaborate instruments for guiding, occulting and refocusing in planetary and lunar photography with extremely high powers—all of these, of any size, refinement, and elaboration desired, each in its own enclosed constant-temperature laboratory, can be used, interchangeably, as desired.

(*e*) In long-exposure photography, direct and spectroscopic, all the mirrors in use, excepting only the coelostat plane mirror, lie in unchanging position throughout the exposure. The same is true of all parts of the telescope mounting, excepting only the coelostat. During a given time of exposure the polar axis of the coelostat rotates only one-half as fast and as far as that of an equatorial telescope. In the present design the entire combined weight of the polar axis, mirror-cell, and mirror of the coelostat is supported directly from underneath by mercury flotation; this gives incomparable smoothness of rotation, and at the same time a very high degree of freedom from flexures of the coelostat. All these conditions, and many others, give to this type of telescope a degree of stability of adjustment and alignment of all parts, optical and other, which is unique, and is indispensable for the highest attainable perfection of astronomical photography and of astrophysical work.

(*f*) All astronomical photographers know the advantages of quick, safe, and accurate interchange of mirrors and of accessory instruments, especially with large reflecting telescopes. Such interchange enables the astronomer to take the fullest possible advantage of changing exterior conditions with respect to atmospheric definition (atmospheric tranquility and homogeneity), to moonlight, and to partial cloudiness. (Some of my most exquisite celestial photographs were taken between very slowly moving clouds.) In astronomical photography the small focal lengths correspond to low magnifying powers, the intermediate focal lengths to medium magnifying powers, the great focal lengths to high magnifying powers. Not only the varying atmospheric conditions, but also the different kinds of celestial objects to be photographed (differing with respect to brightness and to size), determine what is the most favourable focal length to be used. In astronomical photography it is incomparably better to secure the desired magnifying power by means of the proper mirror-combinations than by the use of lenses of any kind.

With this explanation the reader can readily understand that in order to use with great efficiency the very large, highly refined photographic reflectors which are now possible, a high development of both the *universal* principle (a sufficient number of progressive focal lengths) and of the principle of *quick interchange* is imperative.

The Horizontal, Electrically-controlled Guiding Mechanism

59. As a final illustration of the advantages of this type of telescope let us consider briefly the new, horizontal, electrical guiding-mechanism for direct astronomical photography. This important refinement has already been fully demonstrated in my laboratory. When in actual use on the sky it must reach its highest development when used with the Fixed Vertical Universal telescope. Let us consider first the earlier photographic guiding-mechanism I used in making a series of long-exposure photographs of nebulae and star-clusters with the 60-inch Mt Wilson reflector, 1909–1918. Two of these photographs are reproduced in Figs. 10 and 11. The guiding-mechanism itself is shown in Fig. 12*. The square, metal plate-holder, which takes photographic plates 3½ inches square, is seen at the centre of the picture. Two faint guide-stars are chosen, one as close as possible above, the other below, the field being photographed. These guide-stars are watched closely throughout the long exposure, by means of the two microscopes shown, one above, one below, the plate-holder. At the focal planes of these microscopes are cross-lines of fine spider-web, illuminated by faint, red light. By means of the two guide-screws (with large, milled heads) shown, one at the extreme right, the other at the extreme bottom of the guiding-mechanism, the guide-stars are kept always precisely at the intersections of the cross-lines. Guiding is done by watching *continuously* the better one (usually the brighter) of the two guide-stars; very high magnifying powers are used for the microscopes so that very minute errors of position are visible. These errors are due chiefly to small, rapid changes of atmospheric refraction. On an average, two corrections per second were made with each of the guide-screws, that is, two in right-ascension and two in declination. The function of the second guiding microscope is to enable the observer to detect, and to correct for, slight rotation of the field. This is usually necessary each half-hour

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* G. W. Ritchey, *Astrophys. Journ.* 32 July, 1910 (288).

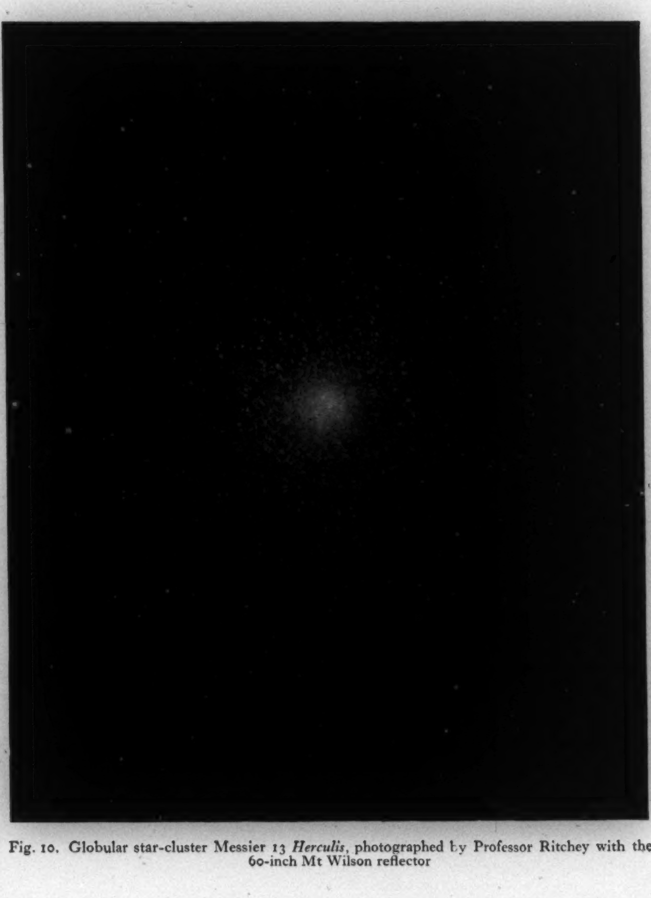

Fig. 10. Globular star-cluster Messier 13 *Herculis*, photographed by Professor Ritchey with the 60-inch Mt Wilson reflector

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Fig. 11. Central part of spiral nebula Messier 33 *Trianguli*, photographed by Professor Ritchey with the 60-inch Mt Wilson reflector

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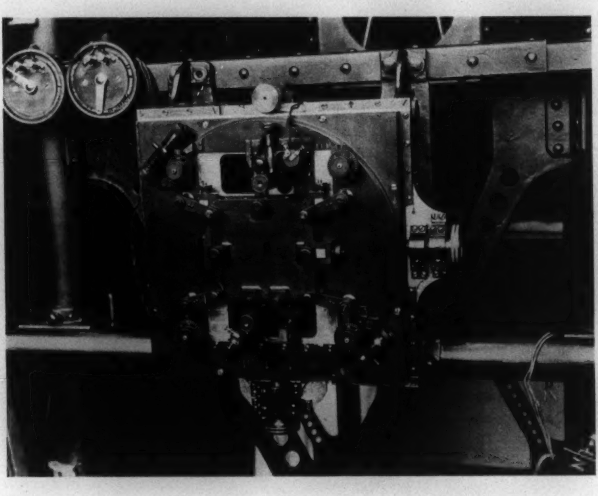

Fig. 12. Double-slide plate-carrier used with the 60-inch Mt Wilson reflector

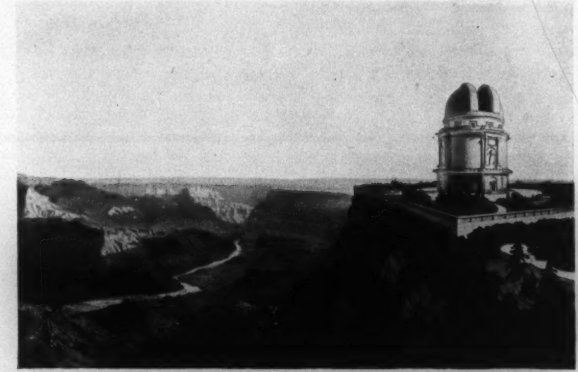

Fig. 13. Project of a future observatory on the rim of the Grand Canyon of the Colorado River in Arizona

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during the exposure; the necessity for it is due to slowly-changing atmospheric refraction, to slightly-changing flexures of the equatorial mounting as it slowly rotates toward the west, and to slight errors of adjustment of the polar axis of the telescope.

60. Equally important is the correction for focus, called refocusing. This is necessary because of slow changes of length of the steel skeleton-tube, and probably of focal length of the mirror, due to slight temperature changes at night; this correction was made each half-hour, by means of the knife-edge focusing device, which permits a degree of accuracy of focusing of 0·001 inch*.

Some Astronomical Photographs made possible by these Refinements

61. With such refinements, with 11 hours' exposure on three successive nights, and with commercial photographic plates ("Seed 23") of moderate speed and fineness of grain, the author was able to photograph 40,520 stars in the globular star-cluster Messier 13 *Herculis* (Fig. 10); the faintest stars shown are of approximately 21·3 magnitude of the Harvard scale, and their photographed images measure 1·03 second in diameter†.

62. In the spiral nebula Messier 33 *Trianguli* (Fig. 11), the author was able to photograph, with 8½ hours' exposure on three successive nights, and with similar photographic plates, 26,430 stars (probably *nebulous stars*) in the convolutions, together with 2350 superposed stars. With this long exposure, 217 *groups* of stars, large and small, most of these groups strongly nebulous, are shown in the convolutions†.

63. The "Seed 23" plates used for the above photographs permit about 10 diameters' magnification or enlargement of the original negatives without the granulation of the emulsion becoming objectionable. Since the focal length of the 60-inch telescope is 300 inches, the original negatives, when enlarged 10 diameters and then viewed at the distance of distinct vision (10 inches) represent a total magnifying power of 300 diameters only. Since the theoretical resolving power of the 60-inch aperture for photographic light (wave-length $0{\cdot}435\,\mu$) and for celestial objects with extended surfaces is about 4275 diameters, we see that in order to photograph celestial objects with theoretical fineness of detail corresponding to this resolving power we must find means for increasing the sharpness of these negatives not less than 14·25-fold‡.

64. With the same telescope and guiding-mechanism I secured many photographs on still finer-grained photographic plate, namely, "Seed Process," the sensitiveness of which is one-third to one-half that of "Seed 23" plates. The granulation of "Seed Process" plates is so fine that it permits magnification or enlargement of the original negatives to 20 diameters, without objectionable granulation becoming visible. For example, my photographs of the annular nebula Messier 57 *Lyrae* and of the bright planetary nebula H. IV 37 *Draconis* permit

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* G. W. Ritchey, *loc. cit.* **32** July, 1910 (287).
† G. W. Ritchey, *Monthly Notices R.A.S.* **70** 1910 (647); *L'Astronomie*, **42** March, 1928 (123).
‡ G. W. Ritchey, *L'Astronomie*, **42** May, 1928 (225, pars. 54–62).

enlargement of 20 diameters from the original negatives; these enlargements, when viewed at the distance of distinct vision, correspond to a total magnification of 600 diameters. Even these photographs are very far from showing the fineness of detail which is theoretically possible with this aperture, namely, the detail due to a total magnification of 4275 diameters.

65. We see from these examples that the quality of granulation of the photographic plate plays a large part in the quality of the resulting negatives. But the reader will see more and more clearly, in the few remaining pages of this paper, the necessity of *all* the refinements which I have continually emphasised, if we are to utilise in astronomical photography the full resolving power of our telescopes. The making of special, fine-grained, highly sensitive emulsions is one of the most important of these refinements*.

ASTRONOMICAL PHOTOGRAPHY WITH VERY HIGH POWERS

66. We should note in regard to the advances already made in astronomy through the application of photography: first, that we can photograph, with long exposures, very much fainter stars, nebulae, spectra, etc., than we can see directly with the aid of the greatest telescopes; second, that in general we can secure much greater accuracy by sound methods of measurement of properly made photographs than by measurements made directly with the telescope and micrometer; third, that many applications of photography to astronomical problems, such as those of solar research, of spectrography, of photometry, of the discovery and study of faint variable stars and *new stars* (*novae*), of photography with ray-filters, and many other applications are of very great importance.

We should note, also, that little has hitherto been accomplished in the direct photography of extremely *small* details of *bright* celestial objects, such as small, very bright planetary nebulae, the planets, and the Moon. These marvellous, small details can be detected *visually* with great telescopes, with very high magnifying powers, on the finest nights, at instants of exquisite atmospheric definition. But to *photograph* these finest details successfully requires a high development of mechanical and optical technique. This development has now been accomplished. Three important points in regard to it should be noted here. First, finer details have been photographed than those which are at the limit of the theoretical, *visual* resolving power of the optical mirrors used; this of course is due to the fact that the photographic resolving power is higher than the visual, in inverse proportion to the wavelengths of the light utilised. Second, the method was gradually developed and completely demonstrated in the laboratory, not on the sky, for reasons which need not be given here. Third, what is of the highest importance, the refinements of methods employed, which include the use of a double-slide practice-machine, are applicable to, and will greatly improve, direct astronomical photography of every kind. This, in turn, will inevitably permit a great increase of accuracy of measurement of astronomical photographs, which is the ultimate purpose of all my efforts in astronomy.

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* G. W. Ritchey, *L'Astronomie*, **42** June, 1928 (290, pars. 102–8).

As a part of this programme I studied visually with the 40-inch Yerkes refractor, and later with the 60-inch Mt Wilson reflector, on the finest nights, the most minute surface-details of the planets and the Moon visible with the full resolving powers of these great instruments*. The best objects for this purpose were found to be extremely minute lunar craters. The smallest craters which could be detected visually were found to be about eight times smaller in diameter than the smallest ones shown in my lunar photographs made with the same telescopes on fine-grained plates, by the method of very short exposures made at selected instants†.

Two principal causes of this large discrepancy were distinctly observed. First, even on the finest nights the minute craters were seen to move continually and irregularly, with reference to the intersection of the fine, ruled cross-lines at the focus of the eyepiece. The *amplitude* of these tremors was usually from two to five times greater than the diameters of the smallest craters, and their *frequency* was such that it was impossible to secure even a very short exposure with the images at rest. It was clear that these tremors were due to minute atmospheric disturbances, and that in order to photograph the smallest details visible a small, very light guiding-mechanism, and extreme speed and skill in its use by the observer, would be required. Perhaps the most surprising feature of this test was that when the cross-lines in the eyepiece were removed, the eye was found to follow, unconsciously, the minute, irregular movements, almost without recognising their presence.

67. The second cause of the large discrepancy is this: even on the finest nights the apparent *sharpness* of the minute details varied continually and quickly when watched with extremely high powers. Frequently they would be seen, sharp and distinct, for two- or three-tenths of a second; much less often for five- or six-tenths of a second; rarely for an entire second. The intervals between these best instants varied, in general, from two to four seconds. The most remarkable fact noticed was that the eye and mind of the observer, keenly intent on seeing the marvellous, minute details visible at the best instants, neglected, *even forgot*, the less favourable instants between. It was only by forcing the attention to note *all* the phenomena that it was seen that the finest instants occupied only one-fifth to one-fourth of the total elapsed time. It was now clear that, in addition to the very rapid guiding, the observer must learn to *expose* and to *cover* the photographic plate with extreme speed and skill, in order to build up the total required exposure at only the instants of finest definition; this would require a very sensitive shutter, which must be very light and well-balanced to avoid all shocks and vibrations.

68. It was clear, also, that the observer could never gain sufficient practice at the telescope on the comparatively few nights of exquisite definition required for photography with the highest powers, and therefore that a *practice-machine* must be designed and constructed, in which the conditions and details observed in the telescope could be closely duplicated mechanically, and with which the observer could gain, by daily practice, the speed and skill required.

69. The first practice-machine for planetary and lunar photography with very

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* For fuller description see *L'Astronomie*, **42** April, 1928 (174).

† G. W. Ritchey, *Decennial Publications, University of Chicago*, **8** 1904 (392).

high powers was designed in 1910, and constructed in my own laboratory in 1918. Its general arrangement was like that of the guiding-mechanism shown in Fig. 12, but it was simpler and very much lighter, and had a highly-sensitive and efficient occulting-shutter, operated by the observer's foot. The artificial images, subject to minute, rapid movements and blurring reproduced artificially with great exactness, were photographed by the observer at the practice-machine precisely as real images would be photographed at the telescope.

70. Systematic practice for two half-hours each day for six months enabled me to more than double the speed of guiding which I had acquired during many years at the telescope; at the same time I gradually learned to use the occulting shutter simultaneously, with great efficiency.

71. In 1919 the general plans of the fixed, vertical, universal telescope were well advanced. These required a *horizontal* guiding-mechanism for the most promising of the component telescopes, the Schwarzschild, Ritchey-Chrétien, and Cassegrainian, the fields of which are horizontal in the universal telescope. In addition, since the field of the Schwarzschild telescope is inaccessible, the advantages of guiding *electrically*, by means of keys operated by the observer's fingers, were studied. The result was the horizontal, electrically operated practice-machine and guiding-mechanism. In this instrument the two slides formerly used are replaced by two very light, rigid frames which roll horizontally, one in right-ascension, one in declination, on hardened steel balls; these balls roll in straight, hardened-steel V-grooves. By these means the small, quick motions of the two guiding frames are practically unopposed by gravity, inertia, and friction, even in the case of very large telescopes and photographic accessories*.

72. After six months of daily practice in the laboratory I was able to use the new, horizontal guiding-mechanism with speed and accuracy more than sufficient to correct for the minute atmospheric tremors and variations of sharpness which had been observed on the finest nights with the 60-inch reflector with a power of 3600 diameters. The continual gain in speed and accuracy was demonstrated daily by actual photographs of the moving and blurring artificial images. It is certain that the smallest details which can be detected *visually* with the 60-inch reflector can now be *photographed*. Further, it is certain that with the same quality of guiding still finer details will frequently be photographed, because of the higher resolving power of the telescope for photographic (blue-violet) light. In addition, the choice of photographic plates sensitive to various colours, together with the use of suitable ray-filters, will enable us to photograph delicate gradations of shading and of colour (of planetary details, for example) which are far beyond the vision of the human eye. All these points have been completely demonstrated in my laboratory.

73. This latest guiding-mechanism and practice-machine illustrate the limitless scope and possibilities of direct astronomical photography. Let us note again, in view of this illustration, that the fixed universal telescope with its stationary, horizontal, non-rotating field, enables us to use all refinements to the utmost limit of their possibilities, under the most favourable laboratory conditions.

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* For a fuller description see *L'Astronomie*, 42 April, 1928 (174, pars. 30 and following).

The following brief paragraphs should be added to the foregoing condensed description:

74. Equally important with the development of better and larger telescopes is the development of special photographic emulsions having simultaneously greater sensitiveness and much finer granulation. This research is already far advanced*.

75. An effort is being made to put all the foregoing technical plans into execution.

76. In order that the refinements and apertures planned shall be *used* with corresponding refinement and accuracy, the daily care of the mirrors and instruments and the actual work of guiding in astronomical photography must be done by specially-trained technicians†.

77. The accuracy and refinement of the machines for measuring the negatives, and the *use* of these machines by trained technicians, must correspond to those of the telescope itself‡.

78. A systematic and efficient search must be made for *sites* for these telescopes, at which atmospheric and climatic conditions are fine enough for their highly efficient use. In general, sites at great altitudes and in extremely dry climates must be chosen§.

79. Telescopes of the apertures planned should be used on the sky at a distance not greater than twelve to fifteen degrees from the zenith of each telescope. This, like the great altitudes, is for the purpose of decreasing the effects of atmospheric absorption and refraction‖.

80. In accordance with the preceding paragraph, the present plan is for a series of five great telescopes, under one management, at latitudes approximately 36° north, 18° north, 0°, 18° south, and 36° south respectively**.

81. Several superlatively fine sites have already been found, through systematic search, for the northernmost unit of this multiple-unit observatory, in the very high, dry plateau-region of the south-western part of the United States. Fig. 13 shows a proposed observatory on the rim of the Grand Canyon of the Colorado River in Arizona, overlooking the Painted Desert to the north. The altitude above sea-level at this point is about 7400 feet.

82. On account of the importance of this subject in fundamental astronomy I give a final and definite example, as follows:

Let us imagine a 7-foot equatorial reflecting telescope of 42 feet focal length, of the best type now in actual use. Let us assume that this telescope is being used for celestial photography by the methods generally employed at present, and that photographs are being made at its Newtonian focus, as at present, for purposes of most accurate measurement—for parallax and proper-motion. Of course it is well known that photographs made at the Newtonian focus of modern, short-focus reflectors are not suitable for most accurate measurement, except for very small fields, because of the coma of all out-of-axis images (see Fig. 6). If, in addition, very large flexures of the telescope tube are present, as in many existing reflectors, even the very small field cannot be utilised with great efficiency.

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* *Loc. cit.* **42** April, 1928 (170); June, 1928 (292, par. 107).

† *Loc. cit.* **42** June, 1928 (281, pars. 85–91).

‡ *Loc. cit.* **42** April, 1928 (170, par. 22).

§ *Loc. cit.* **42** May, 1928 (236, pars. 82–4).

‖ *Loc. cit.* **42** June, 1928 (283, par. 92).

** *Loc. cit.* **42** June, 1928 (296–7).

Further, photographs as at present made at this focus and with this focal length, on commercial plates of very great sensitiveness, permit a maximum, total magnifying power of about 300 diameters to be used in measuring, of which the factor 50 diameters is due to the scale of the photograph, resulting from the focal length of the telescope, and the factor 6 diameters to the magnification given by the eyepiece of the measuring machine. This latter factor is limited by the degree of coarseness of granulation of the photographic plate used. If less sensitive, finer-grained commercial photographic plates are used, such as "Seed 23" plates, a maximum, total magnifying power of 500 diameters can be used in measuring, because we can now use in the measuring machine an eyepiece magnifying about 10 diameters. Frequently, however, photographs as at present made will not permit even *such* magnification, because of inaccurate guiding and focusing, of irregularities of the glass surfaces of the commercial photographic plates used, which prevent accurate focusing, of flexures and distortions of the optical mirrors, of very large flexures of the telescope tube, and so on.

But the theoretical resolving power for fields of stars, due to the 7-foot aperture, is not less than 10,000 diameters*. In this definite example which we are considering, and with the methods of construction and of operation in general use at present, practically *five per cent.* of the real optical power due to the aperture is utilised.

83. In the 5-metre, fixed universal telescope the star-images given by the Schwarzschild and Ritchey-Chrétien aplanatic combinations of mirrors (the only ones used) are practically diffraction discs only, over the entire fields needed for measurement. At the best observatory sites now found, and with the many extreme refinements of guiding, focusing, protection from injurious effects of flexures, of temperature changes and so on, made possible by the fixed type of telescope, together with the greater focal length used for photographs intended for most accurate measurement (a focal length of 200 metres as compared with 12·8 metres used with the 7-foot reflector just considered), it is certain that photographs frequently can be secured which will permit a magnifying power to be used in the measurement of them which corresponds to the full photographic resolving power for star-images, due to the 5-metre aperture, namely, 23,500 diameters†.

In closing, I emphasise that the purpose of the five inventions named in the first paragraph of this paper is to enable us not only to construct, and to operate with convenience, photographic telescopes of very great apertures, but also to *utilise* for astronomical measurement the full theoretical resolving powers due to these apertures.

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* *L'Astronomie*, **42** May, 1928 (228).

† *Loc. cit.* **42** May, 1928 (228, par. 63).

A TRICHROMATIC COLORIMETER WITH SPECTRAL PRIMARIES

By W. D. WRIGHT, A.R.C.S.

MS. received, 19th April, 1928. Read and discussed, 14th June, 1928.

ABSTRACT. The paper describes a trichromatic colorimeter that has been specially designed in order to make an accurate re-determination of the locus of the spectral colours in the colour triangle for as many observers as possible. A spectrometer system is used in which two spectra are formed from the same source. From one of these, three portions to act as primaries are reflected back through a lower part of the dispersing system, so that the mixing of the three radiations is effected by neutralising the prismatic dispersion by which the colours were first separated. From the other spectrum the test colour and a desaturating colour are selected and mixed in a similar manner, and the composite beams are then brought into the two halves of a simple bipartite field. In the process of being mixed with the other colours, each spectral colour is filtered by its return passage through the dispersing system and the instrument thus becomes very effective in removing stray light. Another device has enabled the Maxwellian method of observing the field of view to be adopted without the introduction of rotating parts into the system. The intensities of the three primaries are controlled with photometer wedges.

INTRODUCTION

THE colorimeter to be described has been designed and made in order to carry out some researches on colour vision for the Medical Research Council. The research is being conducted in the Technical Optics Department of the Imperial College and the particular work in view is the accurate re-determination of the locus of the spectral colours in the colour triangle for as many observers as possible.

In this paper the instrument alone is described; no mention is made of the method of calculating the results nor of the results themselves. Some preliminary knowledge of the principles of colorimetry is necessary, however, before the requirements of a comprehensive trichromatic colorimeter can be properly understood, but as these have been clearly outlined in the course of a paper by Mr Guild in 1926* the reader is referred to that paper for the necessary information. In that paper it will be seen that what is required for the work in hand is, first, some arrangement for illuminating one half of a photometric field with a mixture of three primary colours in any desired proportions; secondly, a method to illuminate the other half of the field with any spectrum colour; and thirdly, to desaturate this spectral colour with some other colour (which may be one of the primaries) so that the two together can be matched.

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* J. Guild, "A Trichromatic Colorimeter suitable for Standardisation Work," *Trans. Opt. Soc.* **27** 1925–6 (106).

THE OPTICAL SYSTEM OF THE COLORIMETER

The simplest way to explain the principles of the colorimeter will be to consider one or two properties of the ordinary spectrometer system. Such a system is shown in Fig. 1 (*a*). In connection with this and subsequent diagrams it must be realised that no attempt has been made to draw them to scale. To do so would have resulted in the figures being made so big as to become clumsy if the important details were to be made at all clear. In Fig. 1 (*a*) *S* is the collimator slit, *C* the collimating lens, *A* the spectrometer prism, *T* the telescope objective and finally *RGB* represents the spectrum formed in the focal plane of *T*. Three pencils of rays corresponding to three points, *R*, *G*, and *B*, in the spectrum are shown. These pencils are diverging from one another but the point of divergence can best be traced by reference to the enlarged diagram Fig. 1 (*b*). This shows part of the course of the central rays of the three pencils. It will be seen that after refraction at the first surface of the prism these rays diverge from *O*; after refraction at the second surface they radiate from some point *P* and after passing through the telescope objective they appear to diverge from *P'*, where *P'* is the virtual image of *P* formed by the objective *T*. The position of *P'* is also indicated in the top diagram Fig. 1 (*a*).

Suppose, now, that a concave mirror were placed in the plane of the spectrum and suppose also that the radius of curvature of the mirror were equal to *P'G*. In these circumstances the centre of curvature could be made to coincide with *P'* and the central rays of all the pencils would then fall normally on to the surface of the mirror. They would, therefore, be reflected back along their own paths. In retracing their paths the divergence of the pencils would be neutralised and the beam would emerge from the first surface of the prism as a parallel bundle of white light similar to the bundle of light which originally left the collimating lens. There is an interesting corollary to this, namely, that if the point *P* were situated at the focus of *T* then *P'* would be at infinity and the central rays would emerge parallel after passing through the objective. In this case a plane mirror in place of the concave mirror could be used to reflect the beams back along their own paths.

So far only the divergence of the beam in the horizontal plane has been considered; in this plane the divergence arises from the dispersion produced by the spectrometer prism. But if a slit is used in the collimator the pencils of light will also diverge in the vertical plane owing to the length of the slit. Before passing through *T* these pencils will radiate from the collimating lens *C* and after refraction through *T* they would appear to diverge from the virtual image of *C* formed by the telescope objective. Hence, if it were necessary for the rays of light to retrace their paths exactly, a different curvature for the mirror would be required in the vertical plane from that needed in the horizontal plane. In practice such a refinement is found to be unnecessary.

The next step in the development of the system is to consider the effect of blocking out parts of the concave mirror. The result will be that some parts of the spectrum are cut off, whilst others are reflected back to emerge as a parallel beam, and the colour of the beam will no longer be white but will be the colour resulting from the mixture of the reflected portions. This, then, provides a method of separating any portions of the spectrum desired and re-combining them by neutralising the dispersion by which they were first separated.

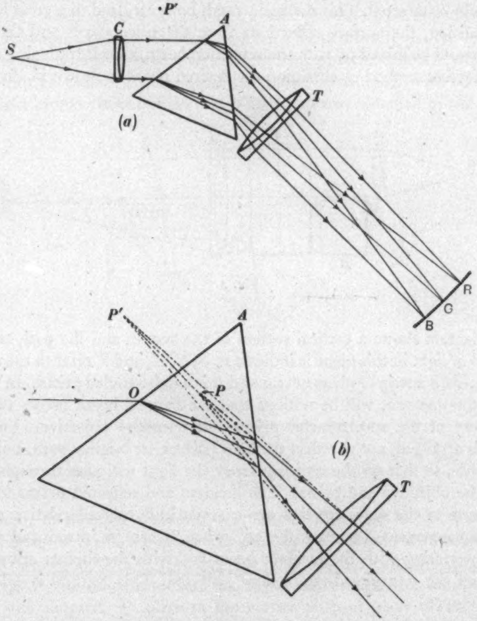

Fig. 1

It is but a short step from the use of a concave mirror with parts blocked out to the employment of narrow strips of plane mirror mounted on arms which rotate about *P′*. Provided that the strips are fairly narrow, the effect of their being plane instead of concave may be neglected. For the case when *P* is at the focus of *T* and therefore *P′* at infinity, the strips of mirror would have to move on a straight slide instead of on the arc of a circle.

It will be readily realised that to use the system as it has been developed so far some difficulty would be experienced in separating the reflected from the incident beam. Both would traverse the same parts of the prism and objective and it would be necessary to introduce a parallel plate of glass, possibly half silvered, into the path of the beams. By inclining this plate at 45° to the direction of the returning beam, this light would be partially reflected and a separation of the two beams would be effected. This method would, however, lead to a great loss of light and, in addition, the surface reflections from the prism faces and the telescope objective would be mixed up with the returning beam, thus introducing stray light. A more effective method of obtaining the desired result is shown in Fig. 2.

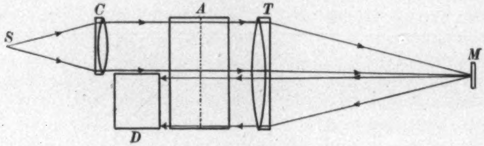

Fig. 2

This diagram shows a vertical section of the system and the path taken by an axial pencil of light in this plane is indicated. *S*, *C*, *A*, and *T* refer to the same parts as in Fig. 1. *M* is a strip of plane mirror and *D* is a right-angled prism. In the system shown in this figure it will be noticed that the parallel beam passes through the upper halves of the spectrometer prism and telescope objective. Further, the mirror *M* is arranged, not to reflect the light back on its original path, but to deflect it downwards, so that on the return journey the light will pass through the lower halves of the objective and prism. The incident and reflected beams in fact pass through parts of the objective that are symmetrically placed relative to its axis. With the arrangement described the 90° prism *D* can be introduced without in any way interfering with the incident beam and with the further advantage that the whole of the returning beam can be reflected. This method is evidently the one to be adopted.

In Fig. 3 the system is taken a stage further. The diagram shows a plan view of the path of an axial pencil of rays. It must be borne in mind that there are really two layers to the system, the returning beam passing beneath the incident beam. In this diagram the action of the prism *D* is shown and the positive lens *O* is introduced. This represents the objective of the observing telescope. In the colorimeter itself the photometer prism is placed between *D* and *O*, but for the present that has been omitted. The Maxwellian method of observing the field of view is used, that is, the eye is placed at *E* where the beam of light comes to a focus. The size and shape of the field seen under these conditions depend on the diaphragm which is effective in limiting the size of the parallel bundle of light before entering *O*.

The image formed at *E* is that of a slit. This is evident since *E* and *M* are in conjugate planes, as are *M* and *S*. Moreover, the image at *E* will not alter in form, however much of the spectrum is reflected back; thus, if the concave mirror originally postulated were placed in the spectrum the image would still be that of a slit, for it has been shown that the nature of the beam after the dispersion has been neutralised is exactly similar to the beam when it first emerges from the collimator. Unfortunately, when the eye is placed at a slit focus the field of view assumes a streaky appearance. Such an effect renders the field practically useless for accurate colour matching. What is needed is an exit-pupil of appreciable area in which a small metal stop can be placed, and be completely filled with light. With such an exit-pupil the field of view is smoothed out. This result was obtained in the first place by introducing a wheel of lenses into the system. The effect of this was to spread out the slit image at *E* into a band and so provide a satisfactory exit-pupil. A somewhat more elegant method of reaching this end was, however, thought of, and as the new scheme was very simple and had several advantages over the rotating lens system, it was adopted. In place of the narrow strip of plane mirror which was previously used in the spectrum, a small right-angled prism is mounted with its hypotenuse face facing the incident light. The pencils of light after total reflection at the two adjacent faces of the prism retrace their paths as before, except that the light which entered on one side of the prism emerges on the other and vice versa. The significance of this will be more easily grasped when it is realised that the principle on which the instrument depends for mixing the spectral colours is the neutralisation of the dispersion by which they are separated. But, for the strip of the spectrum included by the prism, the relative positions of the spectral colours are reversed so that the dispersion over this strip is no longer neutralised but is increased.

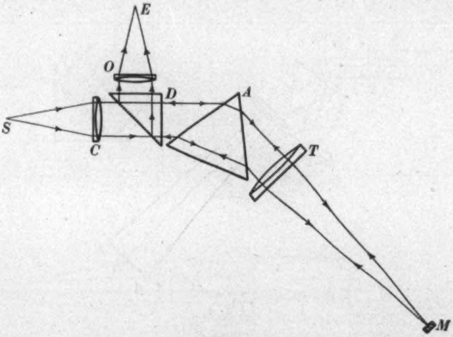

Fig. 3

In Fig. 4 (*a*) three prisms are shown in three parts of the spectrum and it will be evident that their introduction does not interfere with the mixing of the three separate portions of the spectrum in which they are placed. In Fig. 4 (*b*) the action of a single prism is shown and from this it will be seen how the relative positions of the spectral colours are reversed over the portion of the spectrum included by it. The exit-pupil now takes the form of short superposed strips of spectrum with angular dispersions double that pertaining to the corresponding parts of the main spectrum *RGB*. When a metal stop is placed in such an exit-pupil, a smooth field is seen provided the stop is filled with light. By using this arrangement any rotating parts in the apparatus are avoided. In passing it is important to note that the width of spectrum included in the light reaching the eye depends, not on the size of the prism in the spectrum, but on the size of the stop in the exit-pupil.

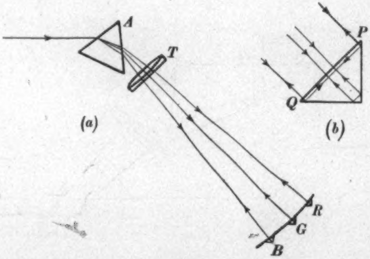

Fig. 4

Up to the present the various features of the system have been described separately. It is now a relatively simple matter to give a description of the colorimeter as a whole. In Fig. 5 both plan and elevation of the complete system are shown, and the course of an axial pencil of rays is also indicated. The source, condenser, collimator, and spectrometer prisms will be easily recognised; they are indicated by the same letters as in previous diagrams. Incidentally, it will be seen that two 60° prisms are used in order to obtain increased dispersion; in all there are four such prisms, two more being used for the returning beam, as will be seen in the elevation. After passing through these prisms the top half of the beam passes through the objective T_1 and is brought to a focus to form a spectrum at W_1. The lower half of the beam is reflected through an angle of 90° by the prism R_1 and is brought to a focus by T_2, so producing a second spectrum at W_2.

In W_1 two right-angled prisms are mounted to function as previously described. The path taken by the light reflected from this spectrum is shown in the elevation and is seen to pass below R_1 and above another prism, R_2, similar to R_1. In W_2 there are three small prisms to reflect back three portions of the spectrum. The light so reflected passes through T_2 and is then reflected by R_2 through the two lower 60° prisms. The two returning beams, from W_1 and W_2, are then reflected by D, so as to fall on the photometer prism P. The form of P and its action will be clear from the figure. It consists of two prisms cemented together, with one half of the contact surface, *mn*, silvered. In this way the two beams are brought into the neighbouring parts of a simple bipartite field separated by a sharp horizontal dividing line, the size of the complete beam being limited by the rectangular aperture K. The field of view is observed by placing the eye at the focus E of the telescope objective O.

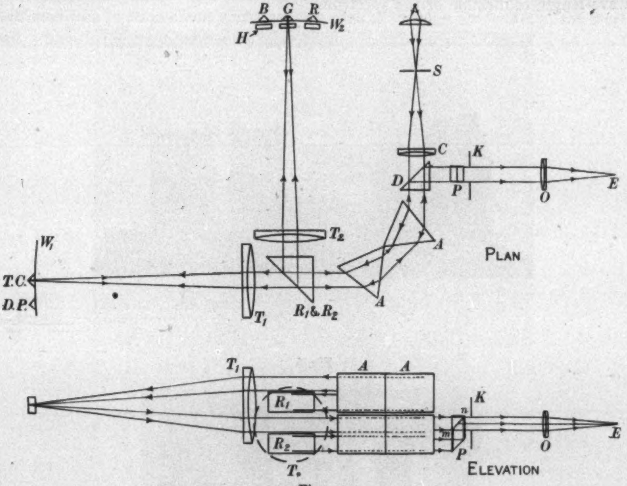

Fig. 5

It will be evident that the three prisms at W_2 correspond to the three primaries of the colorimeter, and the two prisms at W_1 provide the test colour and the desaturating colour. It is necessary to be able to regulate the intensity of the two latter and this is done by the use of any one of a series of neutral filters placed in front of the prisms. Since the variation of the intensity of the primaries must be continuous, neutral photometer wedges, H, are employed, as indicated in the diagram. These are situated in front of the three primary prisms R, G, and B in the spectrum at W_2 and can be adjusted by the observer as explained later.

THE DESIGN OF THE APPARATUS

The source of light used is a 100 C.P. Ediswan "Pointolite" lamp. In the circuit for this lamp a variable resistance and a voltmeter are included so that, during any series of results, the lamp can be run at a constant voltage. The slit of the collimator opens symmetrically, so that a change in its width will not alter the wave-length calibration of the spectrum.

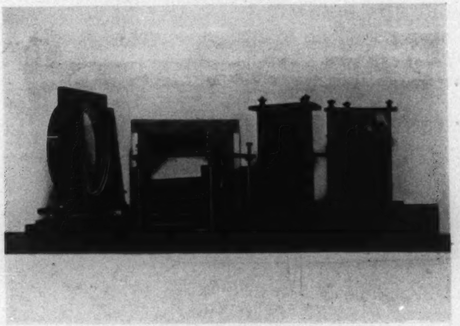

Fig. 6

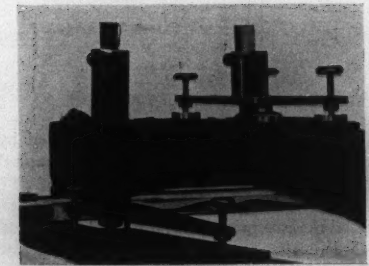

Fig. 7

Fig. 6 is a photograph of part of the apparatus. In this the spectrometer prisms and the telescope objectives can be seen, also the two prisms R_1 and R_2 of Fig. 5. The objectives have a focal length of about 45 inches and with them a spectrum roughly 9 inches long is obtained. Fig. 7 shows the mounting of the small prisms in the spectrum W_1. With this mounting a tilting or rotatory adjustment can be given to the prisms and, since the stands are geometric, the prisms can be removed and replaced later without needing any readjustment. The base-plate of each mounting is attached to a wooden beam about 5 feet in length. One end is pivoted about a point corresponding to P' of Fig. 1. The pivot consists of a large steel ball resting between two conical bearings and the beam is thus allowed to rotate about any axis passing through the centre of the ball. At the other end of the beam two small steel balls are mounted beneath a wooden cross-piece and are allowed to rest on a horizontal surface. In these circumstances the movement of the beam is restricted to a rotation about a vertical axis passing through the centre of the steel ball, which is the required degree of freedom.

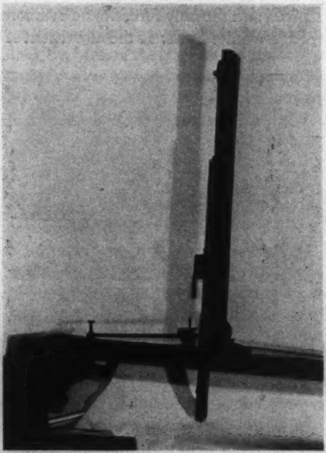

Fig. 8

The prism mountings in W_2 are similar to the above, but there are some additional features which differ in the two spectra. The mountings in W_1 are provided with slots so that any filter that may be desired can be placed in the path of the beam; further, a scale and pointer are arranged for each of these arms in order that the positions of the prisms in the spectrum may be calibrated and subsequently set at any desired wave-length. On the other hand, no wave-length scale is provided for the primaries, but fine adjustment clamps have been fitted to enable the prisms to be accurately set and clamped in the desired part of the spectrum. These clamps act in very much the same way as the tangent screw of the ordinary spectrometer and are designed so that they do not upset the geometric principles used in mounting the radial arms.

Fig. 8 shows the mounting of one of the photometer wedges. The wedges are inserted in rectangular brass fittings suspended from pulleys pivoted at the tops of three aluminium pillars. These pillars are screwed down to the radial arms immediately in front of the prism mountings. Each pillar is arranged to slope forward slightly so that the wedge mounting rests against its inclined face and will slide up or down when the string is moved. Guides are provided to keep the wedges in the proper vertical line and each mounting has a scale and pointer engraved on it to register the position of the wedge at any setting. To move the wedges the strings are led via further pulleys to three drums mounted in front of the observer. The strings are wound round the drums in one direction, whilst in the other direction are wound strings attached to counter-weights. In this way the weight of each wedge mounting is balanced and the only forces to be overcome to move the wedges are frictional forces, which are quite small. If the movement of the drums is too easy, the bearings of the drum spindles may be tightened. In this way a nice motion of the drums, which is very necessary to ensure the peace of mind of the observer, can be obtained. To each drum a knurled head is fixed and the position of the three heads is such that both hands can be used in adjusting them. This is advantageous and tends to shorten the time required to make a match. The positions of the drums and the observing telescope are shown in Fig. 9.

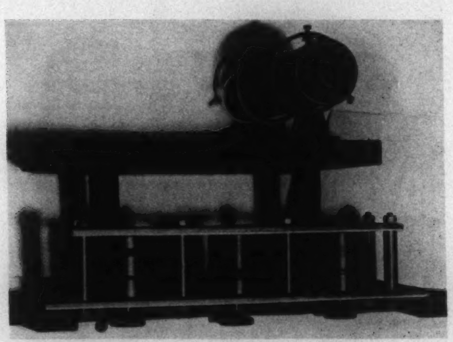

Fig. 9

The telescope has an objective of focal length about 11 inches and the stop in the focus consists of a circular hole in a brass disc. Various stops are available, the one at present in use having a diameter of ·033 inch. With this stop the width of spectrum included is ·0060 μ in the red, ·0035 μ in the green, and ·0016 μ in the blue. The mounting of the telescope is such that the direction of its axis can be altered until the stop is filled with light. The type of adjustment provided is evident from Fig. 9.

The size of the photometric field is $\frac{3}{8}$ inch square and this subtends an angle of about 2° at the eye; with this size of field the image formed on the retina will fall entirely within the fovea. This avoids complications which might arise owing to the variation in structure of different parts of the retina and is in accordance with suggestions made by Mr Guild on the standard size of field to use in colorimetry*. The use of a simple bipartite field is desirable, because one of the chief difficulties in such an apparatus as this is to secure a strictly uniform field. Without such, any more complicated type of field is bound to lead to confusion and to add to the difficulties of colour matching.

For certain purposes not discussed in the present paper a white of some known spectral energy distribution is required. A 1000 watt lamp standardised at the National Physical Laboratory and a filter of two solutions made up in accordance with specifications from the same laboratory were therefore installed, the necessary apparatus being supplied by Messrs Adam Hilger, Ltd. With this, a magnesium oxide screen can be illuminated with light of an energy distribution similar to that of a black body radiating at 5000° K. A small geometric mounting for the magnesium screen was made so that it could be readily brought into the field of view when desired.

ADJUSTMENTS

Little need be said of the adjustments which had to be made when the apparatus was first set up. Much attention had to be paid to the mounting of the various units relative to one another, otherwise the size of some of the parts, such as the telescope objectives, would have been undesirably large. Particular reference need only be made to the location of the centres about which the radial arms rotate. This is really a matter of small import since the introduction of the prisms into the spectrum, but when the apparatus was first assembled strips of plane mirror were used. With this arrangement the centres had to be located accurately and this was done experimentally by altering the position of the centre until, on moving the arm through the spectrum, the reflected patch of light seen in the observing telescope with the photometer prism removed remained stationary.

There are certain adjustments which have to be made with some regularity, so that a description of the method adopted to readjust the apparatus when out of adjustment is given. The test colour prism must first be tilted so as to reflect the beam back on the proper level in accordance with Fig. 5. Apart from securing total reflection, no rotation of the prism about a vertical axis is necessary, as the light will automatically take the required path in the horizontal plane. This is one of the minor advantages of the use of prisms instead of mirrors. The prism which provides the desaturating colour is now adjusted in the same way.

The next step is to adjust one of the primary prisms so that it has approximately the required inclination to the vertical. This is followed by tilting and rotating the large right-angled prism R_2 (the requisite mechanical devices are provided) until the images of the primary and test colour prisms coincide at the focus, *E*, of the observing telescope. Generally the primary prism will need a further slight tilting adjustment, but this will not upset the coincidence of the exit-pupils. The other two primary prisms now only need to be set at the proper inclination to the vertical to complete the adjustments at this end of the instrument.

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* J. Guild, "A Critical Survey of Modern Developments in the Theory and Technique of Colorimetry and Allied Sciences." *Proc. Opt. Convention*, 1926 (61).

At the other end all that remains to be done is to set the prism *D* so that the patches of light fall on the photometer prism in the desired position and finally to adjust and clamp the observing telescope so that the metal stop is completely filled with light in the desired part of the exit-pupil.

CALIBRATION

To calibrate the "test colour" spectrum, a Hilger "constant deviation spectrometer" is mounted at the observing end of the instrument with the ordinary slit attachment removed and replaced, by suitable disposition of the spectrometer, by the exit-pupil of the colorimeter itself. On looking into the eyepiece of the spectrometer an elliptical image of the exit-pupil is seen. The position of this image depends on the wave-length of the light of which it is composed, but by rotating the wave-length drum it can be made to lie symmetrically on the cross-wire in the eyepiece. Provided the drum reading for sodium light has been checked, the reading on the drum will give the mean wave-length corresponding to a given position of the radial arm in the spectrum. To check the drum reading the exit-pupil must be filled with sodium light; this can be done by placing a sodium flame in the orange part of the spectrum. Then when the cross-wire is set on the image of the exit-pupil, the reading of the drum should correspond to the mean sodium line; if any error exists it must be removed by adjusting the Hilger spectrometer prism. When this check has been made the calibration is only a question of noting the drum readings for given positions of the prism on the spectrum scale.

When the calibration has been made as above, throughout the spectrum, a further check is performed. The Hilger spectrometer is removed and the slit of the colorimeter is illuminated with some source such as a mercury lamp, which gives a few well-defined spectral lines. If the test-colour prism is moved through the spectrum until the light from one of the lines is reflected back, an image of the line will be formed at the focus of the observing telescope. The position of the prism is noted when this image passes through the middle of the exit-pupil. The reading of the test-colour scale then corresponds to the wave-length of the spectral line being used, so that an accurate check on the calibration can be obtained very readily. The actual accuracy obtainable in setting the prism is about ·0002 μ, which corresponds to about 1/10 mm. on the scale.

To fix the primary prisms the wave-lengths that are to be used for the primaries must first be decided. When this has been done the Hilger spectrometer is set up as before and at the same time the test-colour prism is put at the wave-length of whichever of the primaries is being adjusted. The position for this is known, of course, from the earlier calibration. With the apparatus so set up two ellipses are seen in the eyepiece of the spectrometer, one corresponding to the test-colour prism and one to the primary. Then all that needs to be done is to move the arm of the primary until the two ellipses coincide and to clamp the arm in that position. The final setting and clamping is done with the fine adjustment attachments. The other two primaries are fixed in a similar manner.

It has been mentioned in the introduction to this paper that the desaturating colour may be one of the primaries, if desired. In practice it greatly simplifies the work to make use of this fact, as an intensity match instead of an auxiliary colour match is all the work that is involved in measuring the desaturating colour introduced. In this case the only calibration needed for the desaturating prism is the determination of the positions of the primary wave-lengths on its wave-length scale. To do this, a method similar to that used for the primaries themselves is adopted.

The remaining calibration is that of the photometer wedges. One half of the field of view is illuminated with light from the primary whose wedge is to be calibrated and the other by light of the same wave-length from the test-colour prism. A sector with a variable aperture is placed in the path of the first of these beams so that its intensity may be varied by known amounts, and a filter is placed in front of the test-colour prism to control the intensity of the other half of the field. The two fields are then matched for a series of sector openings, by adjusting the photometer wedge. In this way the wedge may be calibrated over the portion used in making such a series of matches. To calibrate another portion of the wedge a new filter is placed in front of the test-colour prism and matches are again made for the same series of sector openings. To enable a continuous calibration curve to be drawn the filters are so chosen that the calibrated portions of the wedge overlap, six or seven steps usually being sufficient for the complete calibration of a wedge.

The wedges at present in use are of the gelatine on glass type, as supplied by Messrs Ilford Ltd.; they have a density range of 1½, but as the light passes through them twice the range on the instrument is 3. This is over a length of 6 inches. As the density at the thick end of the wedge is insufficient to cut out the light completely, at least for the red and green primaries, an auxiliary filter is placed in the paths of these beams when the amount required in the match is very small. This filter has to be calibrated when used, but this is very simple, two intensity matches, with and without the filter, being all that is necessary. Small geometric mountings are provided to hold the filters.

STRAY LIGHT

A vital point in an instrument of the present kind, if the results obtained are to be reliable, is that errors due to stray light must be avoided. To achieve this with any success with an ordinary piece of apparatus is difficult, but in this case the colours of low intensity, such as the blue, have to be quite free from stray light although the system is being illuminated with light of much higher intensity from the middle part of the spectrum. The methods employed to overcome the difficulties involved are described in the present section, the extreme importance of the subject being sufficient justification for devoting a separate section to their description.

At first sight it might appear that the type of colorimeter that has been described is especially susceptible to errors from this cause, for the following reason. Some of the light forming the spectrum is intercepted by the small prisms, but the majority passes on until, sooner or later, it falls on one surface or another, and this surface will scatter the light in various directions and may thus be a serious source of stray light. Suppose, for the purposes of the discussion, that a white card were placed in the focussed plane of the spectrum. The light would be scattered in all directions and some of it would return through the instrument and would evidently be brought to a slit focus in the exit-pupil. Fig. 10 shows the rectangular exit-pupil that is obtained with the prism in the spectrum. Bearing in mind that this is an image of the prism, it is fairly evident that the slit exit-pupil obtained with the card will fall on the middle line of the prism image. Hence if the metal stop were placed symmetrically in the exit-pupil, the stray light from this source would be included and would invalidate the results. If, on the other hand, the stop were placed on one side, as indicated by the circle in the diagram, this stray light would be cut out and no longer reach the eye. This then is the first precaution that is taken in adjusting the instrument.

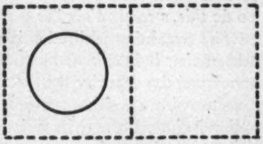

Fig. 10

Even with this precaution some light from the card might be scattered by dust particles, etc., thus introducing stray light of a second order, which might be of sufficient magnitude to affect the results were the white card placed in the spectrum as postulated above. In practice, of course, it is arranged that the light falls on surfaces which are least likely to scatter light back through the system. Thus where glass surfaces, such as the photometer wedge faces, intervene, they are tilted so that the surface reflections are not directed towards the instrument. Other surfaces on which the light falls are blackened. A further important feature which is responsible for the freedom of the instrument from stray light is that the returning beam passes through a part of the apparatus which is not used by the incident light. Were this not possible the apparatus would almost certainly be a failure. Finally it should be pointed out that the presence or absence of stray light from the above causes can be definitely tested for. All that has to be done is to remove all five prism mountings from the radial arms and examine the field of view for stray light. In making such an examination the eye should be dark adapted, else small quantities of light will easily pass unnoticed. This test has been carried out on several occasions and it is a most satisfactory feature of the instrument that no stray light can be detected in this way.

Unfortunately this does not prove that stray light from all sources is absent, for it may well happen, in fact it almost certainly must happen, that the monochromatic light which falls on the prisms in the spectrum will have some scattered light of other wave-lengths mixed with it. But for one fact this might be a source of error difficult to remove. The saving feature can be understood by considering the course taken by a pencil of white light reflected back from the spectrum. On passing through the spectrometer prisms this pencil will be dispersed and in the plane of the exit-pupil a spectrum will be focussed. But owing to the dispersion, the stray light admitted by the exit-pupil will be of the same wave-length as the monochromatic light which is intentionally reflected back and will thus in no way affect the results. In effect the optical system, besides mixing the various monochromatic beams, also acts as a filter to purify each individual beam. This is an extremely useful property of the instrument, although quite accidental so far as the author is concerned. No method has been evolved of testing its effectiveness directly, but it cannot be open to much doubt.

One further precaution has been taken, which may be understood by reference to Fig. 10 again. In this it is seen that the metal stop was placed unsymmetrically in the patch of light forming the exit-pupil. If the colour in the two halves were appreciably different, any light scattered from the unused portion would tend to upset the results; to prevent this happening a system of diaphragming would be required which would cut out one half of the exit-pupil. The method adopted is not ideal, but has proved satisfactory; it is shown in Fig. 11. This diagram shows the paths of some of the rays as they enter and leave one of the small prisms in the spectrum. It is evident that if one half of the prism were blocked out, then the whole beam would be cut off; but with the diaphragm in the position shown, where the incident and reflected beams no longer overlap in the vertical plane, it is possible to cut off one half of the beam without interfering with the other. Such a position is not ideal because the diaphragm is not sharply in focus in the plane of the exit-pupil. This, however, is largely counteracted by the narrow divergence of the pencils of light between the spectrum prism and the diaphragm.

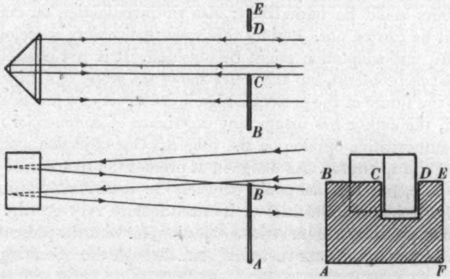

Fig. 11

APPLICATIONS OF THE INSTRUMENT

One evident application is as an instrument for research on colour vision. Its three chief virtues in this connection are the absence of stray light, the high intensity available in the field of view, and the use of spectral primaries which have the advantage that they are easily defined physically. It must also be remembered that in its present form the apparatus is more than a trichromatic colorimeter, for it provides both halves of the photometric field.

With these points in mind it may be well to mention some of the problems which could be tackled with such an instrument with, in some cases, small modifications in the design. Thus the hue sensibility curve for a number of observers could be determined; a determination of the number of saturation steps between the spectral colours and white or what may be called the saturation sensibility curve for the spectral colours could be undertaken; also an investigation on complementary colours could be carried out. Besides this, quantitative data on colour blindness, colour fatigue, and adaptation might be obtained. It is not possible to give an exhaustive list of problems, but the above shows the scope of the instrument.

So far as the future of the present design in its aspect of a practical colorimeter is concerned, the author has insufficient experience of commercial requirements to voice an authoritative opinion on the subject. One objection would doubtless be the size of the apparatus. As designed at present the instrument covers a fair amount of space, but the size could probably be considerably reduced without increasing the technical difficulties of its manufacture very greatly. The size of the exit-pupil is probably a more serious objection, for with the present diameter of ·033 inch the intensity of dark materials seen through the observing telescope is rather low.

In such a case it is an advantage if the size can be varied by using, say, a small iris diaphragm, but with this system any variation in the size of exit-pupil involves a change in purity of the primaries. Such a procedure would therefore be objectionable. With the original system, in which a wheel of lenses was employed, a variable exit-pupil could be used and it may be that a satisfactory instrument for commercial work could be designed on those lines.

Apart from their use in a colorimeter the principles involved in the apparatus may have some use in connection with other instruments. For example, a form of constant deviation spectrometer could be designed; or by using a mirror instead of a prism in the spectrum any portion of the spectrum could be concentrated into a slit image; this might be of use in energy problems when the energy present were small. For any such purposes the instrument would have the advantage of being free from stray light.

In conclusion I have to acknowledge with gratitude my great debt to Professor L. C. Martin for having on my behalf approached the Medical Research Council, to whom I am also greatly indebted, with a view to securing a grant to enable me to undertake the research. In addition several features of the apparatus are due

directly to Prof. Martin and many modifications are the result of his valued help and advice. Also, my warmest thanks are due to Mr R. H. Colborne, who during the later stages has given valuable assistance with the work that remained to be done, and, with the apparatus completed, has taken an equal share in the observational part of the work. Lastly I wish to refer to the frequent recourse that has been had to Mr J. Guild's papers in the *Transactions* of this Society and in the *Proceedings of the Optical Convention*. These have been extremely useful, both on the theoretical and the practical aspects of the subject, and have undoubtedly had a modifying influence on the design of the colorimeter.

DISCUSSION

Prof. L. C. Martin: I should like to congratulate Mr Wright on the successful completion of this instrument in the building of which he has shown so much ability, and also to express my gratification that through the help of the Physiological Optics Committee of the Medical Research Council (and especially of Sir John Parsons) it has been possible to commence anew the important work of Abney and Watson in the convenient room which they themselves designed and used. I look forward with hope for results of great interest and value.

Mr J. Guild: The author is to be complimented on the skill and ingenuity with which he has attacked the many difficulties involved in the design of apparatus of this type. There are only two points which I think call for criticism. The first of these is the use of gelatine wedges to control the intensities. I have used wedges for this purpose and have found that they require frequent re-calibration owing to changes which take place in the gelatine. Further, after some time, local irregularities tend to develop and these are very difficult to eliminate by calibration.

This is really the outstanding difficulty in constructing a colorimeter with spectral primaries: no really satisfactory method of controlling their intensity has been evolved. Varying the width or length of the slits, as has been done by some of the earlier workers, is useless for precise work, while with apparatus of any reasonable size the primary slits are too close together to allow the interposition of variable rotating sectors in front of each. This makes it necessary to resort to wedges, with the drawbacks just mentioned.

The second point to which criticism may be directed is the use of a fairly wide slit, or its equivalent, at the observer's eye. This is immaterial as regards the primaries themselves, but as regards the monochromatic beam of which the colour is to be measured it is desirable to be able to employ very narrow slits at some parts of the spectrum to eliminate uncertainty as to the slit width correction for the wavelength. The author may find when he comes to the actual working out of his spectral mixture curves that it is desirable to restrict his slit width and re-introduce the rotating lens spreader to obtain the desired width of exit-pupil.

Despite these points the instrument should be a very useful research tool, and the subsequent publication of results obtained with it will be awaited with interest.

As a general colorimeter for use in industrial laboratories an instrument of this type has, however, many disadvantages. Many of the adjustments and calibrations which would have to be made from time to time with such an instrument are only possible in a research laboratory, requiring auxiliary equipment for the standardisation of wave-length, photometric transmission, etc., which would not be available in an industrial laboratory. Colorimeters with coloured filters as primaries have the advantage that, when once calibrated at a standardising institution, nothing which can affect the essential constants of the apparatus can possibly go wrong for a very long time.

Mr R. Kingslake (communicated): Mr Wright is to be very heartily congratulated on this extraordinarily ingenious colorimeter, and particularly on the many neat devices he has thought of to overcome the various difficulties which he encountered. I had the privilege of watching the instrument grow in its early stages, but many of the parts are new. Especial mention should be made of his idea of using small reflecting prisms instead of bits of flat mirror, to remove the streakiness of the field and to make accurate rotational adjustment of the little reflectors unnecessary. I should however like to ask what is the width of these prisms, or rather what length of spectrum is reflected by them? Surely these bands are too broad to be considered as providing strictly monochromatic primaries?

The author has very well emphasised the importance of removing stray light, and some of his methods are extremely ingenious, displaying a very intimate knowledge of the underlying action of the whole instrument. Another point which he has considered very carefully is experimental comfort; this is of course important in any research, but especially so in photometric or other critical visual work. I may add that Mr Wright not only designed all his apparatus but also made much of it himself in the College workshop.

In conclusion I must express admiration at the clearness and completeness of the whole description, with the hope that Mr Wright will shortly be able to contribute further papers on the various applications to which he can put the apparatus.

Mr Wright: Mr Guild rightly points out that the gelatine wedges need frequent re-calibration and whilst this is inconvenient it is a difficulty which has to be overcome at the expense of a certain amount of time. When permanent local irregularities develop, the wedges will have to be replaced by new ones. The use of black glass wedges would be an improvement and would be a necessity for instruments of a more permanent nature than the present one.

With regard to the uncertainty introduced by the use, as the test colour, of a beam which is not strictly monochromatic, the magnitude of the error will need investigation and, if greater than can be tolerated, it will either be necessary to determine a correction curve, or eliminate the error by some instrumental modification.

In reply to Mr Kingslake's query, the size of the prism in the spectrum does not determine the range of wave-length that is included in the beam entering the eye; the determining factor is the size of exit-pupil, as is pointed out in the course of the paper.

NOTE ON THE USE OF LENSES IN SERIES FOR SIGHT TESTING

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MS. received, 16th May, 1928. Read, 14th June, 1928.

ABSTRACT. The paper deals with the theory of a train of lenses placed in series as used in a trial frame or other instrument. The series arrangement enables a small number of lenses to be combined to give the correction for any regular defect of form. It is shown that in general effective powers are not simply additive, but under conditions described in the paper the error made in regarding them as additive becomes small. The conditions involve the order of the lenses and the position of every lens except the first of the train. It is always possible to satisfy these conditions in a system designed for use in the way described. With incorrect arrangements serious errors may be made.

In trial frames provision is made for the use of two or three lenses in series, placed as nearly as may be where a spectacle lens would be worn. The use of lenses in series is essential to the construction of a system suitable for any eye that may have to be examined. This is at once apparent if the number of lenses necessary to enable every combination of sphere and cylinder to be represented is considered. But there is no need to stop at the stage where the spherical powers are represented by one element and the cylinders by another: considerable economy may be effected by using several lenses in series. This is strikingly illustrated by Sir George Stokes' observation nearly eighty years ago that two cylindrical lenses suffice for the measurement of all degrees of astigmatism. In a trial frame the use of two cylinders would be inconvenient, but the objection would hardly apply to the use of this device on more elaborate instruments such as have been produced recently.

So considerable a simplification is not attainable with spherical lenses. Nevertheless in theory, if several lenses may be used in series, few are needed. An arrangement which has been employed for this purpose is based on a property of the well known arrangement of numbers given in Table I.

Table I

1	2	3	... $(n-1)$
n	$2n$	$3n$	... $(n-1)n$
n^2	$2n^2$	$3n^2$	... $(n-1)n^2$
n^3	$2n^3$	$3n^3$	... $(n-1)n^3$

....

By simple addition, taking not more than one number from each row (of which we suppose there are r), we can obtain all integers from 0 to $(n^r - 1)$. The number of finite elements out of which these n^r integers are constructed is $(n-1)r$. Disregarding for a moment the disturbing effect of the thicknesses and separations, so that powers are simply additive, we infer that n^r powers in arithmetical progression can be obtained with $(n-1)r$ lenses if we are prepared to use as many as r lenses in series. As an illustration suppose it is required to form by combination all positive powers from 0 to 15·75 D. in steps of 0·25 D. The number of powers, including zero, is 64. The last column of Table II shows the total number of lenses required for various values of r.

TABLE II

n^r	r	n	$(n-1)r$
64	1	64	63
64	2	8	14
64	3	4	9
64	6	2	6

Clearly, though there may be strong objections to the use of as many as six spherical lenses in series, the advantages obtainable from the superposition of two or three are great. This is exhibited in a different form in Table III, which gives the number of different finite powers obtainable with $(n-1)r$ lenses according to the scheme of Table I for various values of n and r.

TABLE III

$n-1$		1	2	3	4	5	6	7	8	9	10
$r =$	1	1	2	3	4	5	6	7	8	9	10
	2	3	8	15	24	35	48	63	80	99	120
	3	7	26	63	124	215	342	511	728	999	1330
	4	15	80	255	624	1295	2400	4095	6560	9999	14640

It should be observed that this table gives the number of combinations attainable in an instrument in which the lenses are set in r fixed parallel planes, each plane containing $(n-1)$ lenses and a blank. It does not in general give the total number of consecutive powers attainable by the superposition of $(n-1)$ lenses not more than r at a time. To take a simple example, with four lenses and $r = 2$, the table indicates that 8 finite powers are obtainable: on the other hand with four lenses of powers 1, 2, 4, 7 used singly or in pairs the first integral power absent is 10.

An important optical question remains. It is impossible to place more than one lens in the position that would be occupied by a spectacle lens; all the others must be farther from the eye. If the lenses are made to yield correct results when used singly, is the effective power of a combination represented accurately by the sum of the effective powers of the constituent lenses, and if not is the discrepancy of serious magnitude? We proceed to consider this question on the supposition that any given lens, if used, is always placed at the same distance from the eye, a hypothesis that can always be satisfied if the various powers are built up in accordance with the scheme of Table I.

The only optical relation needed for the discussion of this question is the equation connecting the positions of conjugate foci along the axis of an instrument.

If x and x' are conjugate distances measured in the same direction for any two origins, the equation is of the form

$$axx' + bx' - cx - d = 0 \qquad \text{......(1)},$$

where

$$bc - ad = 1 \qquad \text{......(2)}.$$

If both origins are moved in the positive direction through the same distance ξ, we have to write $x + \xi$ and $x' + \xi$ for x and x', and hence find for the new coefficients

$$\left.\begin{aligned} a' &= a \\ b' &= b + a\xi \\ c' &= c - a\xi \\ d' &= d - (b - c)\,\xi - a\xi^2 \end{aligned}\right\} \qquad \text{......(3)}.$$

Such a change evidently leaves $b + c$ in addition to a and $bc - ad$ unaltered; we may therefore suppose the original origins chosen so that b and c are equal. Moreover, if we make the two origins coincident any shift of origin will be of the type to which equations (3) apply. In dealing with combinations of lenses we shall find it convenient to take the centre of the spectacle lens as the common origin. Referred to this point the four coefficients of any trial lens can be denoted by

$$\alpha,\ \beta + \alpha\xi,\ \beta - \alpha\xi,\ \delta - \alpha\xi^2 \qquad \text{......(4)},$$

where

$$\beta^2 - \alpha\delta = 1.$$

Remembering now that all origins are common, equation (1) gives for the coefficients of the combination of two systems

$$\left.\begin{aligned} a_{1,2} &= a_1 b_2 + c_1 a_2 \\ b_{1,2} &= b_1 b_2 + d_1 a_2 \\ c_{1,2} &= c_1 c_2 + a_1 d_2 \\ d_{1,2} &= d_1 c_2 + b_1 d_2 \end{aligned}\right\} \qquad \text{......(5)}.$$

If X and X' are the curvatures of the incident and emergent wave-fronts at the common origin, equation (1) may be written

$$a + bX - cX' - dXX' = 0,$$

showing that if the object is so distant that we may put $X = 0$ the curvature of the emergent wave-front is equal to a/c. We are therefore chiefly interested in the value of a/c for a compound system as given by (5). It will be convenient to denote this ratio for any system by the single letter γ. Equations (5) give immediately

$$\gamma_{m,n} = \sum_{p=m}^{n} \gamma_p \frac{c_p}{c_{p,n}\, c_{p+1,n}} \qquad \text{......(6)}.$$

In computing the second factor the ratio d/c, or say ϵ, enters into the formula. The equation by which ϵ for a combination can be computed is

$$\epsilon_{m,n} = \Sigma\epsilon_p \frac{c_p}{c_{m,p-1}\, c_{m,p}} \qquad \text{......(7)}.$$

It is quite a simple matter by the aid of these equations together with

$$\frac{c_{1,2}}{c_1 c_2} = 1 + \gamma_1 \epsilon_2$$

to show that in an instrument of the kind we are contemplating in which all the lenses are of the same sign

$$\gamma_{m,n} > \Sigma\gamma_p,$$

that is to say, if the instrument is always correct when only a single lens is in use, the real effective power of a combination will be algebraically greater than the nominal effective power. The magnitude of the error will increase as $\Sigma\gamma_p$ increases in absolute magnitude, and the important question therefore relates to the magnitude of the error for the high powers.

Instead of using equations (6) and (7) for the computation it is simpler to note from (4) that

$$\frac{b}{c} = 1 + 2\gamma\xi \quad \text{and} \quad \frac{d}{c} = \frac{\delta}{c} - \gamma\xi^2.$$

Now for a single lens of thickness t the value of δ may readily be shown to differ by a very small quantity from $t\left(1 - \frac{1}{\mu}\right)$, where μ is the refractive index of the glass. As the thickness of any lens intended for series use ought to be small, δ should always be negligible in the expression for d. Moreover, if the lens is equiconvex or equiconcave ξ is measured from its centre, and if one of the surfaces is plane ξ is measured from a point within the glass distant $\frac{1}{2}\delta$ from the curved surface. In effect this means that we can treat the individual lenses as thin. The formula for the computation of γ now becomes

$$\gamma_{1,2} = \frac{\gamma_1 + \gamma_2 + 2\gamma_1\gamma_2\xi_2}{1 - \gamma_1\gamma_2\xi_2^2} \qquad \text{......(8).}$$

In this expression the ξ necessarily relates to a single lens, and the γ for the series is therefore to be built up by adding the lenses one at a time in the order in which they are encountered by the incident light.

By considering first a system of two components, we see, as is also evident from (5), that ξ_1 does not appear in any expression in which we are interested: in other words, the position of the first lens is immaterial. Another important deduction is that no error is introduced by inserting a final lens after any correctly calibrated system provided the former is in the position which would be occupied by a spectacle lens. As a special case the errors should always be zero when only a single spherical lens and a single cylinder are used simultaneously provided both trial frame and trial lenses are correctly designed. We also deduce that any lenses which are sensibly displaced from the spectacle position when three or more components are used should be of low power; that is to say the light should meet the weakest lenses first and the most powerful lenses last.

It would be expected that the order of lenses is only material when their separations are negligible, but this may not be considered an obvious conclusion from the rule for finding the power of a compound thin lens, for we are throughout concerned with effective and not real powers. It is, however, readily found from (8) that if $\xi_2 = \xi_3 = \xi_4 = \ldots = \xi_r = \sigma$ the equation for $\gamma_{1,r}$ becomes

$$\gamma_{1,r} = \frac{\Sigma p \, S_p \sigma^{p-1}}{1 - \Sigma \, (p-1) \, S_p \sigma^p} \qquad \text{......(9)},$$

where S_p denotes the sum of all homogeneous products of $\gamma_1, \gamma_2, \ldots \gamma_r$ taken p at a time when repetitions are excluded; since the S's are independent of the order of the elements the order of the elementary lenses only becomes important when the differences of the effective distances from the spectacle centre of the component lenses are taken into account.

A distinction between the properties of the effective power of this system and the true power of a thin system is seen at once in the presence of S's other than S_1. The importance of the additional terms will depend on σ and on the number of lenses present. Since according to Table I the combination of highest power is formed of elements whose powers are in geometrical progression, we will suppose that we are dealing with a series of r lenses, whose effective powers form a geometrical progression of common ratio ρ, the nominal power of the combination being κ, so that $\kappa = S_1$. For the geometric progression $1, \rho, \rho^2, \ldots \rho^{r-1}$ it may be shown that

$$(\rho^p - 1) \, S_p = (\rho^r - \rho^{p-1}) \, S_{p-1}$$

from which it follows that in (9) we should substitute

$$S_p = \kappa^p \cdot \frac{\rho^r - \rho}{\rho^2 - 1} \cdot \frac{\rho^r - \rho^2}{\rho^3 - 1} \cdots \frac{\rho^r - \rho^{p-1}}{\rho^p - 1} \cdot \left(\frac{\rho - 1}{\rho^r - 1}\right)^{p-1} \qquad \text{......(10)}.$$

The most important term affecting the error is that involving the first power of σ. We have as a very approximate formula on neglecting squares and higher powers of σ

$$\gamma_{1,r} \bumpeq \kappa \, (1 + 2Q_r \kappa\sigma) \qquad \text{......(11)},$$

where

$$Q_r = \frac{\rho^r - \rho}{(\rho^r - 1)(\rho + 1)} \qquad \text{......(12)}.$$

The symmetry of Q may be exhibited by putting $P = \rho + \dfrac{1}{\rho}$. We then obtain

$Q_1 = 0$, $Q_2 = \dfrac{1}{P+2}$, and generally

$$Q_{2k-1} = \frac{1}{1+P-}\,\frac{1}{P-}\,\frac{1}{P-} \cdots \frac{1}{P}$$

and

$$Q_{2k} = \frac{1}{1+P-}\,\frac{1}{P-}\,\frac{1}{P-} \cdots \frac{1}{P-}\,\frac{1}{P+1},$$

the number of fractions with denominator $P-$ being $k-2$ in both expressions. Clearly it is advantageous for P to be large, that is, ρ either large or small. The value of r is of minor importance. It is worth noting that Q lies between 0 and $\frac{1}{2}$.

We have now to take into account the difference between the ξ's of successive lenses. It will be sufficient to consider only the first powers of these effective separations. If we understand by S_p^q the sum of the homogeneous products p at a time of the first q γ's, we find at once from equation (9)

$$\gamma_{1,r} \bumpeq S_1^r + 2S_2^2(\xi_2 - \xi_3) + 2S_2^3(\xi_3 - \xi_4) + \ldots + 2S_2^{r-1}(\xi_{r-1} - \xi_r) + 2S_2^r\xi_r \qquad \text{......(13).}$$

It will be convenient to retain σ as the distance of the last lens from the spectacle position, and to determine the influence of the separations by writing

$$\xi_2 - \xi_3 = \xi_3 - \xi_4 = \ldots = \xi_{r-1} - \xi_r = \tau,$$

leading to an equation of the form

$$\gamma_{1,r} \bumpeq \kappa(1 + 2Q_r\kappa\sigma + 2R_r\kappa\tau) \qquad \text{......(14).}$$

The value of Q_r has already been found, but that of R_r depends on the order in which the lenses are arranged. We will suppose that they are arranged in the order of the geometrical progression, so that the effective power of any lens is ρ times that of its immediate predecessor. We then find

$$\begin{aligned} R_r &= \frac{\rho}{(1+\rho)(1-\rho^r)^2}\left[r - 1 - \frac{(1-\rho^{r-1})(1+\rho+\rho^2-\rho^r)}{1-\rho^2}\right] \qquad \text{...(15)} \\ &= \frac{r\rho\{(\rho+1)Q_r - 1\}^2 + (\rho^2+2\rho-1)Q_r - \rho}{(1-\rho)(1-\rho^2)}. \end{aligned}$$

The last expression will only be used for calculations when the Q's have been evaluated. From (15) if we suppose ρ large

$$R_r \bumpeq \rho^{-3} \qquad \text{......(16),}$$

but if all the lenses are reversed in order, which is equivalent to replacing ρ by its reciprocal,

$$R_r \bumpeq (r-2)\rho^{-1} \qquad \text{......(17).}$$

The contrast between these results shows the great importance of placing the lenses in their right order.

An idea of the value of R for moderate values of ρ may be obtained from the value for $\rho = 1$, viz.

$$R_r = \frac{(r-1)(r-2)}{6r} \qquad \text{......(18)}$$

which suggests that it is not unimportant to keep r small.

Special values of importance are

$$R_3 = \frac{Q_3^2}{\rho} = \frac{1}{(P+1)^2\rho} \qquad \text{......(19)}$$

and

$$R_4 = \frac{Q_4}{P(P+1)}\left\{1 + \frac{1}{\rho} + \frac{2}{\rho^2}\right\} = \frac{1}{P^2(P+2)}\left\{1 + \frac{1}{\rho} + \frac{2}{\rho^2}\right\} \qquad \text{......(20),}$$

which obviously agree with (16), (17), and (18). We may infer from these values that with closely packed lenses the error due to separations need not be serious with a proper arrangement of the lenses, but may be much too great to neglect under other conditions.

As a check on the reliability of these approximate formulae it is only necessary to inspect the remaining coefficients. At the same time, since lenses of considerable thickness are sometimes used in sight testing, it may be useful to include the δ of (4) which has hitherto been neglected. We may reasonably assume that those thicknesses which are not negligible can be represented by supposing that the lenses, if worked to a sharp edge, would be bounded by a circle of constant radius *e*. Then, applying the ancient rule that the semi-aperture is a mean proportional between the thickness and the focal length, we have

$$e^2 = \frac{t}{a}, \text{ or } \frac{d}{c} = \gamma\,(\eta - \xi^2), \text{ where } \eta = e^2\left(1 - \frac{1}{\mu}\right)$$

and is thus the same for all the lenses. Using this value of *d*/*c* we find in place of (9)

$$\gamma_{1,r} = \frac{\Sigma\Sigma\, S_p \binom{p}{2q+1} \sigma^{p-2q-1}\,\eta^q}{1 + (\eta - \sigma^2)\,\Sigma\Sigma\, S_p \binom{p-1}{2q+1} \sigma^{p-2q-2}\,\eta^q},$$

and the approximate equation (14) is not altered. To find the exact equations we write Σ, T, and H for $\kappa\sigma$, $\kappa\tau$, and $\kappa^2\eta$ respectively. Then for a combination of two lenses we obtain

$$\frac{\gamma}{\kappa} = \frac{1 + 2Q\Sigma}{1 - Q\,(\Sigma^2 - \mathrm{H})}, \text{ where } Q = \frac{1}{P+2};$$

for a combination of three lenses

$$\frac{\gamma}{\kappa} = \frac{1 + 2R\mathrm{T} + 2Q\Sigma + Q^3\{(\Sigma + \mathrm{T})\,(3\Sigma - \mathrm{T}) + \mathrm{H}\}}{1 - R\mathrm{T}\,(2\Sigma + \mathrm{T}) - Q\,\{1 + 2Q^2\,(\Sigma + \mathrm{T})\}\,(\Sigma^2 - \mathrm{H})} \quad \text{......(21)},$$

where

$$Q = \frac{1}{P+1}, \quad R = \frac{Q^2}{\rho};$$

and for a combination of four lenses

$$\frac{\gamma}{\kappa} = \frac{\begin{array}{c} 1 + 2R\mathrm{T} + 2Q\Sigma + U\{(\Sigma + \mathrm{T})\,(3\Sigma - \mathrm{T}) + \mathrm{H}\} + V\mathrm{T}\left\{2\Sigma - 3\mathrm{T} + \dfrac{6\Sigma + 5\mathrm{T}}{\rho}\right\} \\ + 2U^2\{(\Sigma + 2\mathrm{T})\,(2\Sigma^2 - \mathrm{T}^2) + 2\,(\Sigma + \mathrm{T})\,\mathrm{H}\} \end{array}}{\begin{array}{l} 1 - R\mathrm{T}\,(2\Sigma + \mathrm{T}) - 2U\dfrac{\mathrm{T}^2}{\rho^2} - 2\dfrac{V\mathrm{T}}{\rho}(\Sigma + 2\mathrm{T})\,(2\Sigma + \mathrm{T}) \\ -\left[Q + 2V\mathrm{T}\left(1 + \dfrac{1}{\rho}\right) + 2U(\Sigma + \mathrm{T}) + U^2\{(\Sigma + 2\mathrm{T})\,(3\Sigma + 2\mathrm{T}) + \mathrm{H}\}\right](\Sigma^2 - \mathrm{H}) \end{array}} \quad \text{......(22)},$$

where

$$U = \frac{1}{P^2\,(P+2)}, \quad V = PU^2\left(1 + \frac{1}{\rho}\right),$$

$$Q = P\,(P+1)\,U, \quad R = U\left(\frac{P+1}{\rho} + \frac{1}{\rho^2}\right).$$

In a properly designed system neither Σ nor T should exceed $0{\cdot}1$ in the worst combination, while H can be kept down to about $0{\cdot}01$; with such values, and p and P as great as 5 or more, the comparative unimportance of other coefficients than those retained in (14) follows.

The general conclusions affecting the magnitude of the error are not altered if the final lens differs in sign from those that precede it.

REVIEWS

The National Physical Laboratory—Report for the Year 1927. Pp. vi + 264; 56 Figs. and Plates. (London: H.M. Stationery Office, 1928.) Price 7*s.* 6*d.* net.

This volume contains the Report of the Executive Committee to the General Board, and the Reports of the Director and Heads of the various Departments for the year 1927. It contains a concise statement of the work proposed for the year 1928–9, tabular statements of the tests carried out in the last three years, and a very useful list of scientific papers by members of the Staff published during 1926–7.

The book is mainly a summary of the manifold activities of the premier research institution of the Empire, but new researches, methods, and devices are described in detail in many cases. The wide field covered by the work of the Laboratory and the great service it renders to other research institutions by furnishing them with the fundamental methods or standard instruments which they require is apparent to anyone who glances at the pages of this *Report*.

It is of value as a record of the present position of research in many fields, and scientific workers generally will find something of interest and profit to them in its pages.

The typography and illustrations are very good—the photographs are worthy of special mention—and there is a good index.

In the report on the Optics Division of the Physics Department a brief account is given of the work done on the new Hilger Universal Lens Interferometer which is illustrated by an excellently reproduced set of eight interferograms of a telescope objective. Research on the properties of asymmetrical lens systems has been continued, and in this connection an investigation has been made as to the extent to which it is possible to correct fully the astigmatic defects of an eye with the aid of spectacle lenses. It has been found that while errors of focussing may be fully corrected, other defects remain, one of which is an effect of the rotation of the image about the axis of the eye. This is not likely to produce appreciable effects in the ordinary use of the eyes, but accuracy in making vernier settings, as in the case of the coincidence rangefinder, may be impaired to a considerable extent.

Colour measurement and standardisation is an important branch of the work of this division, and it is of interest to note that the results of colour measurements are now expressed in terms of two quantities, one of these denoting the *quality* irrespective of brightness and the other the *shade* or degree of brightness irrespective of the quality of the colour.

The work carried out by the Photometry Division of the Electricity Department is both varied and extensive. An account of some of the work in photo-electric photometry has been published in these *Transactions*. Besides work in heterochromatic photometry, and in the maintenance and comparison of light standards, interesting researches having important bearings on everyday life have been carried out. Among these may be cited the measurement of illumination due to sky-light, reflecting factors of road surfaces, and the efficiency of rear reflectors for bicycles.

The report on the Metrology Department refers to the satisfactory progress which has been made towards the establishment of a wave-length standard of length, and there is also an interesting discussion on the difference between the optical and mechanical lengths of end gauges.

Valuable information bearing on the design of instruments and on the methods of testing component parts of instruments is to be found in the reports of practically every department.

W. B. C.

The Theory of Light. By the late Prof. THOMAS PRESTON, M.A., D.Sc., F.R.S. Fifth edition edited by Prof. ALFRED W. PORTER, D.Sc., F.R.S. Pp. xxiv + 643; 271 Figs. (London: Macmillan and Co., Ltd., 1928.) Price 25*s*. net.

Preston's *Theory of Light* was written at a time when the study of optics was regarded more than nowadays as an academic pursuit in the realms of Natural Philosophy. The subject has since taken a position of increasing importance in the general body of science and technology, but no general book to satisfy all requirements has recently been written. The attempt to bring up to date a book so well written as Preston's is therefore justified and has met with success in the fifth edition, edited by Prof. A. W. Porter.

Important additions to the previous work have been made in the treatment of thick lenses, the theory of aberrations, the analysis of spectral lines by the interferometer, the resolving power of instruments, and Michelson's method of measuring stellar diameters.

Deletions have been made of a number of theorems concerning Fresnel integrals, as being of slight practical importance, and of mathematical and historical, rather than of physical interest.

Improvement has been effected by a rearrangement of the account of the theory of diffraction, and various minor changes, tending to clarity, have been introduced.

Improved by all these changes, Preston's work, newly edited, still deserves a prominent place on the shelf of the advanced student of physics.

D. S. P.

ABSTRACTS OF PATENT SPECIFICATIONS

275583*. Telefunken Ges. TELEVISION APPARATUS.

A beam of light passes through a cell containing a glass ball immersed in nitro-benzene of nearly the same refractive index as the glass. Electrodes between which a variable potential is applied produce changes in the refractive index of the material, and vary the intensity of the transmitted beam.

275597*. British Thomson-Houston Co., Ltd. PHOTOMETERS.

The light distribution curve of an electric lamp is obtained by employing two photoelectric cells, one subject to the direct light from the lamp, the other to light reflected upon it from a rotating mirror. The currents from the two cells are applied in opposition to a thermionic valve in connection with an oscillograph, the record of which is photographed.

275925*. Westinghouse Brake and Saxby Signal Co., Ltd. SIGNAL LAMPS.

Two lenses having concentric wedge-shaped grooves formed in their outer surfaces are employed to project a parallel beam. A cover glass provided with horizontal prisms is fitted to deflect some of the light downwards, and between this and the adjacent lens opaque concentric cylindrical screens are placed to shield the lamp from light entering from the exterior.

276040. British Power Railway Signal Co., and others. SIGNAL LAMPS.

The lenses are so shaped that, in addition to the main beam, secondary divergent beams are also projected, which merge into the main beam in any manner that may be desired. In one arrangement the main lens is of stepped profile, an auxiliary lens with special ribs being employed to produce the secondary beam.

276059. Aldis, A. C. W. SIGHTING-DEVICES.

An observational instrument includes a system for illuminating a graticule, and an observing telescope of unit magnification, so that an image of the graticule is apparently projected into the plane of the object. The graticule is placed at an angle of 45° between two tubes carrying the principal parts of the apparatus.

276084. Round, H. J. TELEVISION APPARATUS.

A bundle of quartz or glass rods or silvered tubes is massed with one end behind an illuminated picture. The other ends are arranged in a circle, and a sensitive cell upon a rotating arm is carried past each in turn. The varying currents are transmitted to the receiving station, and serve to reconstitute the picture through a similar apparatus.

276324*. Goerz Optische Anstalt, etc. TELESCOPES.

A sighting telescope fitted with erecting prisms has its ocular directed downwards. The entrance opening is rotatable with one of the prism systems about a vertical axis, and the right-angle prism is rotatable about a horizontal axis, the image being maintained upright.

* Specification published before acceptance.

276480. Keeler, C. H. SIGHT-TESTING APPARATUS.

The instrument comprises a tube in which an electric bulb is placed, the light from which can be rendered divergent, parallel, or convergent by a system of lenses which are adjustable in position. The instrument can thus be used as an ophthalmoscope or a retinoscope.

276772. Barr and Stroud, Ltd., and another. RANGEFINDERS.

A screw the pitch of which varies with the range or with the logarithm of the range is employed in setting the deviation prism. The "nut" may be in the form of a roller, pivoted to adjust itself to the varying pitch angle.

276795. Fourcade, H. G. SURVEYING.

In determining the true position of points shown on aerial photographs a stereogrammetric apparatus is employed in which the photographs are held and adjusted until properly placed for viewing by a binocular telescope. Contour drawing apparatus is associated with the optical system.

277467. General Electric Co., Ltd., and others. PHOTOMETRIC APPARATUS.

Photometers for rating electric lamps include two sensitive cells having different characteristics, the ratio of the currents produced in them indicating the efficiency of the lamp tested, which varies with the spectral distribution of the light emitted. The test requires only the taking of two readings of an electroscope corresponding to predetermined voltages applied to the lamp.

277727. Woolley, E. A., and others. VEHICLE LAMPS.

An anti-dazzle arrangement comprises a short cylindrical frame adapted to be clipped over the body of a lamp in front of the glass, and furnished with a number of equally spaced vertical partitions.

277776. Parker, W. VEHICLE LAMPS.

An anti-dazzle and fog penetrating device for attachment to vehicle lamps consists of a screen of coloured calico, preferably yellow, which is furnished with an elastic band to enable it to be sprung over the front of the lamp.

278045. Hurter, A. PROJECTION APPARATUS.

For projecting advertisements on to the clouds an apparatus is employed consisting of a horizontal arc backed by a reflector, which projects light through the slides and the objective on to a mirror inclined at about 45°.

278052. Williams, G. M., and another. LAMPS.

A ship's lamp is described in which the illuminant is a neon tube of a zig-zag form arranged in two planes at an angle, or curved to conform to the general shape of the lamp glass. It may be used in conjunction with colour screens, and the colour may be modified by including a little mercury in the tube.

278149. Williamson, C. M., and another. PROJECTORS.

In an automatic focussing arrangement, the object carrier and the screen are each provided with a cam, and the lens mount is connected with a follower so designed as to be operated by one cam over the enlarging range, and by the other throughout the reducing range.

278335*. Zeiss, C. SURVEYING.

A telescope provided with a rangefinding attachment is associated with a graduated ruler which enables profiles to be plotted by sighting. The ruler may be fixed, and the instrument then used for measuring angles of inclination.

278338*. Zeiss, C. LENSES.

Numerical data are quoted for an objective each half of which consists of a collective meniscus facing the diaphragm and a cemented doublet. The system is corrected for spherical and chromatic aberrations, astigmatism, and coma.

278394*. Darbel, R. J. D., and another. THREE-COLOUR SYSTEMS.

A beam of light passing an objective is divided by an optical system of reflecting prisms, optical compensation being effected so that the resulting images shall all be identical.

278431. Booth, L. B. TELESCOPE SYSTEMS.

Between the objective and the eyepiece an erecting system is placed, which is designed to correct the curvature and astigmatism of the objective, and to obtain accurate registration of two graticules over a wide angular field. The erecting system comprises one or two diverging lenses between two converging lenses, or conversely.

278557. Alder, W. A. PROJECTION APPARATUS.

Three horizontal projectors directed so as to throw intersecting beams of light upon suitable mirrors are employed to project coloured and changing images into space. Two of the beams pass through changing colour filters, the third producing the picture.

278663. Hugershoff, R. STEREOSCOPIC APPARATUS.

An eyepiece for stereoscopic instruments is provided with an adjusting device for regulating the distance between the apertures, and also with independent means for raising one or both of them.

278664. Hugershoff, R. STEREOSCOPIC APPARATUS.

In the optical system of stereoscopic measuring instruments, a change-over device is fitted in order to transpose the beams, so that the normal stereoscopic vision becomes pseudo-stereoscopic.

278893. Heath, G. A., and others. SEXTANTS.

To the frame of a sextant is attached a socket which engages a plug fitting terminating in a ring to carry a telescope, by which means an adjustment of the axis in relation to the horizon glass may be made.

278949. Steele, L. J., and another. PROJECTION LAMPS.

The source is placed at the centre of curvature of a hemispherical mirror, which point is coincident with the common focus of two concentric paraboloidal reflectors. A biconvex lens is placed in the central portion of the beam. Adjustment is made by mounting the elements upon fittings sliding upon a system of carrier rods.

279040*. Leventhal, J. F. OPTICAL SYSTEMS.

An optical system designed to move a beam of light parallel to itself consists in one form of two plane-parallel plates of glass set obliquely upon spindles which are rotated in opposite directions. A single plate, or two plates on one spindle may be employed in conjunction with a prism.

* Specification published before acceptance.

279067*. Westinghouse Electric, etc. Co. TELEVISION APPARATUS.

The analysis of the object is effected by a rotating disc, preferably of stainless steel, upon which are formed a series of concave reflectors which impart a vertical movement to the image. A lateral movement is produced by interposing a rotating prism, of which the angle varies continuously over the whole circumference.

279069*. N. V. Nederlandsche Instrumenten Cie. TELESCOPES.

A sighting telescope for aircraft use carries displaceable graticules consisting of two groups of lines, by means of which the distance and angular deviation of a shot from the target may be respectively obtained.

279243. Heath, G. A., and others. SEXTANTS.

The tangent screw has a single bearing formed in one with a plate pivoted in two bracket pieces. Backlash is eliminated by an adjustable spring plate having a central bearing upon the screw.

279322. Ustonson, C. B. LENSES, FILTERS.

Superimposed layers of glass are pressed while hot between dies so shaped as to press part of one layer into the other. The compound sheet may be ground to produce a bifocal lens, a graduated colour filter, or other similar article.

279457*. British Thomson-Houston Co., Ltd. TELEVISION APPARATUS.

Light from four or more adjacent elements of a picture is projected simultaneously to affect distinct light-sensitive cells, and similar arrangements are included in the receiving apparatus. A revolving system of inclined mirrors working with a spiral series of lenses enables the field to be covered in succession along four or more bands.

279493*. Soc. d'Optique, etc. de Haute Précision. RANGEFINDERS.

In a coincidence rangefinder the altitude of an aerial target is ascertained by effecting the adjustment of the displacement prism by a milled head, the rotation of which is a function of the altitude.

279783. Westinghouse Brake and Saxby Signal Co., Ltd. SIGNAL LAMPS.

The lamp front consists of a glass plate with ribs upon its central portion, and between it and the lens system is placed a series of concentric cylindrical screens. The bulb itself is so arranged that light entering along the axis from an external source is reflected obliquely from it, and intercepted by the screens, thus preventing phantom indications.

R. J. T.

* Specification published before acceptance.

PROCEEDINGS
AT THE
MEETINGS OF THE OPTICAL SOCIETY
1927–28

13th October, 1927

Meeting held at the Imperial College of Science.

Dr R. S. CLAY, President, in the Chair.

The following papers were read:

"Experiments in Ultra-violet Refractometry." By Professor L. C. MARTIN, D.I.C., A.R.C.S., D.Sc.

"The Construction of Wave-length Scales for Spectrograms." By GUY BARR, B.A., D.Sc.

10th November, 1927

Meeting held at the Imperial College of Science.

Dr R. S. CLAY, President, in the Chair.

Elections (Membership): Professor A. OGG and Professor E. A. OWEN.

The following paper was read:

"On the Resolution of Gratings by the Astigmatic Eye." By J. R. HAMBLIN, B.Sc., and T. H. WINSER.

Mr OWEN AVES exhibited his "Deviograph" and trial frame.

8th December, 1927

Meeting held at the Imperial College of Science.

Dr R. S. CLAY, President, in the Chair.

Elections (Membership): Mr T. MARTIN and Lieut. A. C. TARNOW.

It was announced that, on the invitation of the President of the Société Française de Physique, Mr F. C. Dannatt had been nominated by the Council to represent the Optical Society at the Fresnel Centenary ceremony which was held at the Sorbonne from 27th to 29th October. A brief report from Mr Dannatt on the proceedings was read.

The following paper was read:

"The Design of Reflecting Prisms." By Instructor Captain T. Y. Baker, F.Inst.P., R.N.

Mr S. J. Underhill, of Messrs Adam Hilger, Ltd., gave a demonstration of an experiment in piezo-electricity (due to Professor Kerr Grant).

10th, 11th and 12th January, 1928

Eighteenth Annual Exhibition of Electrical, Optical and other Physical Apparatus held at the Imperial College of Science, jointly with the Physical Society.

The following discourses were given:

"Progress in the Recording and Reproduction of Sound." By A. Whitaker, M.A. (The Gramophone Co., Ltd.).

"Recent Applications of X-rays." By V. E. A. Pullin, B.A., O.B.E., F.Inst.P.

"Artificial Daylight." By J. W. T. Walsh, M.A., D.Sc., F.Inst.P.

19th January, 1928

Special General Meeting held at the Imperial College of Science.

Dr R. S. Clay, President, in the Chair.

The following amendment to Rule 102 was proposed by the Council for approval by the necessary quorum of members present in accordance with Rules 61 and 122, due notice in accordance with Rule 58 having been given to all members:

That Rule 102 be altered to read as follows:

"102. The Treasurer's accounts and balance sheet shall be audited and certified by professional auditors. Six weeks at the least before the day appointed for holding the Annual General Meeting the Society shall appoint two members of the Society, not being members of the Council, who shall examine the audited accounts and balance sheet and report thereon to the Society."

The adoption of this amendment was carried unanimously.

19th January, 1928

Meeting held at the Imperial College of Science.

Dr R. S. Clay, President, in the Chair.

Elections (Membership): Mr R. Kingslake, Mr C. W. Laubman, Lieut. A. G. Macdonald, Mr H. G. Pank, Mr T. C. Richards, and Mr C. H. Walters.

(Fellowship): Mr O. Aves, Mr L. Bellingham, Professor L. H. Cooke, Lieut. M. Hotine, Mr C. Kershaw, Mr S. C. Laws, Mr R. Miall, Mr J. W. Ogilvy, Dr J. W. T. Walsh, and Dr A. F. A. Young.

Messrs C. J. Beck and R. W. Cheshire were elected to act as Hon. Auditors of the Society's accounts for the year 1927.

The following papers were read:

"On Toric Lenses." By T. Smith, M.A., F.Inst.P.

"Canonical Forms in the Theory of Asymmetrical Optical Systems." By T. Smith, M.A., F.Inst.P.

Mr G. S. Fawcett, of Messrs The Tintometer, Ltd., exhibited the Rosenheim-Schuster colorimeter, based on Lovibond's colour system.

9th February, 1928

Meeting held at the Imperial College of Science.

Dr R. S. Clay, President, in the Chair.

Announcements were made concerning the Seventh International Congress of Photography to be held in London from 9th to 14th July and the Bibliography of Colorimetry now being compiled by Dr Irwin G. Priest, Bureau of Standards, Washington, D.C., full details of which had been sent to all members of the Society.

Mr D. Baxandall spoke on the visit the members were about to make to the Science Museum to view the historical collection of optical instruments, and illustrated his remarks with lantern slides. Votes of thanks to Mr Baxandall and to Col. Sir Henry Lyons for his permission and the facilities given to make the special visit were unanimously passed. The members and their friends then visited the Science Museum with Mr Baxandall.

16th February, 1928

Meeting held at the Imperial College of Science.

Dr R. S. Clay, President, in the Chair.

Elections (Membership): Mr R. C. Buchanan and Major K. F. Dunsterville.

The following papers were read:

"An Investigation into the Beam from a Standard Lighthouse Lens." By W. M. Hampton, Ph.D., B.Sc., F.Inst.P., A.I.C.

"The 'Absolute' Hartmann Test." By R. Kingslake, M.Sc., A.R.C.S., D.I.C., F.R.A.S.

Dr R. S. Clay exhibited a portable stereoscopic kaleidoscope designed by himself and Sir Richard Paget.

Mr W. O. Clarke gave a demonstration of his optical smoke box.

8th March, 1928

Annual General Meeting held at the Imperial College of Science.

Dr R. S. Clay, President, in the Chair.

The Hon. Secretary presented the Annual Report* of the Council, which was approved.

The Hon. Treasurer presented his Report† and Balance Sheet‡, which were approved.

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* See p. xi. † See p. xiv. ‡ See p. xv.

The Chairman read the list of persons nominated by the Council for office in the year 1928–29 and declared all these duly elected as no other nominations had been received:

President: Dr R. S. Clay.
Vice-Presidents: Mr D. Baxandall, Mr H. H. Emsley,
Mr J. Guild, Mr F. C. Watts.
Hon. Secretary (Business): Professor A. F. C. Pollard.
Hon. Secretary (Papers): Mr W. B. Coutts.
Hon. Treasurer: Major E. O. Henrici.
Hon. Librarian: Mr J. H. Sutcliffe.
Editor of Transactions: Dr John S. Anderson.

Council:

Already serving:	Elected, March, 1928:
Mr E. F. Fincham.	Mr O. Aves.
Mr E. T. Hanson.	Mr T. Chaundy.
Instr. Lieut.-Comdr. N. M. S. Langlands.	Dr C. V. Drysdale.
Professor A. O. Rankine.	Mr A. Whitwell.
Mr H. C. Raxworthy.	
Mr J. Rheinberg.	
Mr R. S. Whipple.	
Col. H. S. L. Winterbotham.	

Votes of thanks to the retiring Officers and Members of Council, to the Hon. Auditors, to the Governors of the Imperial College, with Prof. Callendar, for the use of the College premises for the meetings of the Society, and to Mr Banfield for his assistance at the meetings of the Society were unanimously passed.

8th March, 1928

Meeting held at the Imperial College of Science.

Dr R. S. Clay, President, in the Chair.

Election (Membership): Mr J. Nicol.

Dr Clay delivered his Presidential Address entitled "The Stereoscope." A large collection of stereoscopic apparatus and slides of historical interest was exhibited and numerous demonstrations were given.

16th May, 1928

Meeting held at the Imperial College of Science.

Dr R. S. Clay, President, in the Chair.

Elections (Membership): Miss L. M. Coleman and Dr W. M. Hampton.

Professor G. W. Ritchey delivered the Thomas Young Oration entitled "The Modern Reflecting Telescope and the New Astronomical Photography."

14th June, 1928

Meeting held at the Imperial College of Science.

Dr R. S. Clay, President, in the Chair.

The following papers were read:

"The Errors of a Reflecting Prism." By Instructor Captain T. Y. Baker, F.Inst.P., R.N.

"A Trichromatic Colorimeter with Spectral Primaries." By W. D. Wright, A.R.C.S.

"The Theory of Aplanatic Surfaces." By T. Smith, M.A., F.Inst.P.

"The Primordial Coefficients of Asymmetrical Lenses." By T. Smith, M.A., F.Inst.P.

"Note on the Use of Lenses in Series for Sight Testing." By T. Smith, M.A., F.Inst.P.

Mr W. B. Coutts exhibited a number of slides illustrating studies in diffraction which had been prepared by the late F. W. Shurlock, B.A., B.Sc., F.Inst.P. It was resolved that the thanks of the Society be sent to Mrs Shurlock for her kindness in lending the slides and the notes describing them.

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THE OPTICAL SOCIETY

REPORT OF THE COUNCIL TO THE ANNUAL MEETING OF MEMBERS, 8TH MARCH, 1928

THE COUNCIL of the Optical Society presents the following Report for the year ending 31st December, 1927:

During the year the Annual General Meeting and nine Ordinary Meetings of the Society were held at the Imperial College of Science and Technology by permission of the Governors and Professor Callendar, to whom the thanks and appreciation of the Society are due.

At the Annual General Meeting in February, Dr R. S. Clay was inducted to the Chair as President of the Society, and at the Ordinary Meeting, immediately preceding this, the retiring President, Mr T. Smith, delivered the Presidential Address entitled "Some Uncultivated Optical Fields."

In May an outstanding paper on "Contributions to the History of English Opticians in the First Half of the Nineteenth Century" was presented by Professor M. von Rohr.

The March meeting was entirely devoted to ophthalmological papers arranged by the Sub-Committee referred to in the Report for 1925, and at this meeting Mr Basil Graves gave a lecture on "Microscopy of the Living Eye" and described work of the greatest importance and interest. Unfortunately the interest shown by members in this side of Optics has not yet justified the formation of an Ophthalmological Section.

The maintained demand from outside sources for the *Transactions* is an indication that the Society is continuing to do work which is useful and appreciated. The Council feels, however, that the interest of the discussions on the papers would be enhanced if members attended the meetings more frequently. The subscriptions for membership have been reduced and it is very desirable that the membership of the Society should be increased.

Early in the year, at a Conference of representatives of the Physical Society, the Optical Society, and the Institute of Physics, arrangements were made whereby certain routine work is now undertaken by the Secretary of the Institute of Physics on behalf of the two Societies.

In conjunction with the Physical Society, the Seventeenth Annual Exhibition of Electrical, Optical and other Physical Apparatus was held at the Imperial College of Science and Technology on the 4th, 5th, and 6th of January and was attended by large numbers of people.

During the Exhibition Professor E. N. da C. Andrade, dressed in the costume of the early eighteenth century, delivered a Lecture on Light and Electricity, illustrated with experiments and some of the apparatus used in 1709 by F. Hauksbee, F.R.S., and this achievement was very much appreciated. Dr C. V. Drysdale gave a lecture on "Progress in Electrical Instrument Design and Construction," and Mr J. L. Baird a lecture on "Television."

On the invitation of the President of the Société Française de Physique a delegate of the Optical Society, Mr F. C. Dannatt, attended the ceremony held at the Sorbonne on 27th October to celebrate the Centenary of the death of Augustin Fresnel.

Members were invited to a Conference convened at Liverpool by the Royal Microscopical Society upon the invitation of the University of Liverpool and the Civic Authorities, and Mr J. E. Barnard and Professor L. R. Wilberforce were elected to act as delegates on this occasion.

As in the past, members were invited by the Board of the Institute of Physics to attend the lectures on "Physics in Industry," and the Illuminating Engineering Society have issued invitations to all their meetings.

Mr Whipple has continued as the representative of the Society on the National Committee of Physics, and Dr R. S. Clay has represented the Society on the Board of the Institute of Physics.

In conjunction with the Physical Society, arrangements were made for members of both Societies to travel to Richmond, Yorkshire, to witness the Solar Total Eclipse which took place at 6.24 a.m. on 29th June, but great disappointment was shared with the thousands who had assembled on the Race-course at the appearance of clouds which started to obstruct the phenomenon a few seconds before totality. Afterwards members were given facilities to visit the Minster in York.

Previous to the visit Dr E. H. Rayner gave a lecture at the Imperial College on "The Forthcoming Solar Eclipse." The lecture, to which members were invited by the Physical Society, was very much appreciated.

LIBRARY

In addition to the regular Journals the following publications have been received during 1927:

Proceedings of the Optical Convention, 1926. Parts I and II.

The Optical Convention, 1926: *Catalogue of Optical and General Scientific Instruments.*

Department of Scientific and Industrial Research: Illumination Research, Technical Papers:

No. 4. *Surface Brightness of Diffusing Glassware for Illumination.* By C. J. W. Grieveson, B.Sc., M.A.

No. 5. *The Measurement of Mean Spherical Candle Power.* By the Staff of the Photometry Division, The National Physical Laboratory.

No. 6. *The Natural Lighting of Picture Galleries.*

No. 7. *Penetration of Daylight and Sunlight into Buildings.*

Penrose's Annual: The Process Year Book and Review of the Graphic Arts, Vol. 29. Edited by Wm. Gamble, F.R.P.S., F.O.S.

X-Rays Past and Present. By V. E. Pullin and W. J. Wiltshire.

Photography: Its Principles and Applications. By ALFRED WATKINS, F.R.P.S.

Stars and Atoms. By A. S. EDDINGTON, M.A., D.Sc., LL.D., F.R.S.

Scientific Papers of the Bureau of Standards:

No. 547. *The Lovibond Color System.* I. *A Spectrophotometric Analysis of the Lovibond Glasses.* By K. S. GIBSON and F. K. HARRIS.

No. 548. *Wave-length Measurements in the Arc and Spark Spectra of Zirconium.* By C. C. KIESS.

No. 557. *A Suggested New Base Point on the Thermometric Scale and the* $\alpha \rightleftarrows \beta$ *Inversion of Quartz.* By FREDERICK BATES and FRANCIS P. PHELPS.

Transactions of the Optical Institute in Leningrad, Vol. IV:

No. 34. *Anwendung der Differenzenrechnung auf ein Problem der Diffusionstheorie, im speziellen auf die Diffusion des Lichtes.* By V. A. FOCK. (In Russian.)

No. 35. *Contrôle des miroirs paraboliques par la méthode de Hartmann.* By M. F. ROMANOFF. (In Russian.)

Applied Refraction. By HOMER ERASTUS SMITH.

Professional Papers of the Air Survey Committee:

No. 3. *Simple Methods of Surveying from Air Photographs.* By Lieut. M. HOTINE, R.E.

Einfuhrung in die theoretische Optik. By Dr MAX PLANCK.

Physics in Industry: Lectures delivered before the Institute of Physics, Vol. V:

Lecture X. *The Relationship of Physics to Aeronautical Science.* By H. E. WIMPERIS, O.B.E., M.A., F.R.Ae.S.

Lecture XI. *Physics in Navigation.* By F. E. SMITH, C.B., C.B.E., D.Sc., F.R.S.

Encyclopédie Photométrique. Première section—Généralités. I. *Introduction Générale à la Photométrie.* By CHARLES FABRY.

MEMBERSHIP

During the year thirteen Members, one Corporate Member, and three Student Members were elected. Eight Members resigned, two were removed, and two died. There is therefore an increase of five in the membership of the Society, leaving the number of Members on 1st January, 1928, as follows:

Ex-Officio Fellow	1
Honorary Fellows	10
Fellows	103
Fellows non-resident in British Isles	9
Members	130
Members non-resident in British Isles	30
Corporate Members	9
Corporate Members non-resident in British Isles	2
Student Members	10
Total	304

TREASURER'S REPORT FOR THE YEAR 1927

During 1927 arrangements were made with the Institute of Physics to undertake much of the clerical work of the Society, and the arrangements for the annual exhibition, thus relieving the Honorary Officers of routine work which was increasing, and for which they were finding it increasingly difficult to spare the time. Partly because of this change it was decided to have the accounts audited by professional auditors. At their suggestion a slight alteration has been made in the form of the accounts, and the subscription income shown in the Income and Expenditure Account for 1927 is the amount *due* for the year. The arrears of subscriptions received during 1927 have been shown separately, and the amount outstanding for 1927 has been shown among the debts due to the Society in the balance sheet. In previous years the amount of subscriptions actually received, including arrears, has been included in the income for the year and subscriptions owing have not been shown. There are actually still some arrears due for 1926, which may be recovered, but they have not been shown as an asset. Allowing for this alteration in the form of the accounts, the income is slightly less than for last year.

The expenditure at £766 is slightly lower than last year (£775), if the cost of the 25-year index which was issued in 1926 is omitted from the comparison, but is slightly above the normal. The cost of printing the *Transactions* is about normal, and is less than last year which was unusually high. The items which show an appreciable increase are those for clerical assistance and sundries. These increases are due to the new arrangement with the Institute of Physics. The Exhibition receipts, which are the Society's share of the excess of receipts over expenditure definitely chargeable to the Exhibition, must be set off against the payments to the Institute of Physics for clerical assistance. Arrangements have been made by which, in future years, the Exhibition receipts will cover the cost of the clerical and organising work involved. Sundry expenses include a sum of £12. 2*s*. 6*d* for filing cabinets, etc. required by the Institute of Physics for the storage of the Society's documents.

In 1925 the Society guaranteed £200 to the Optical Convention, and advanced this amount as a loan. Though the accounts of the Convention are not yet finally closed, there will be a considerable loss, and 75 per cent. of the guarantee fund has been called up. This £150, which appeared as an asset in the 1926 balance sheet, has now been written off, leaving £50 as a loan to the Optical Convention.

Apart from the £50 above mentioned, the assets shown in the balance sheet are all liquid assets, and nothing has been included for the value of the books, stock of publications, or furniture, though these are insured against loss by fire for £300.

There have been no changes during the year in the Society's investments, or in the life compositions account.

E. O. Henrici,
Hon. Treasurer.

18th February, 1928.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDING 31st DECEMBER, 1927

Dr EXPENDITURE

	£	s.	d.	£	s.	d.
To Printing and Stationery:						
Printing and distributing *Transactions*	494	8	4			
Office printing and stationery	36	3	11			
				530	12	3
Clerical assistance:						
Editorial expenses	59	10	5			
Other expenses (including £56. 5*s*. 0*d*. payment to Institute of Physics)	91	5	9			
				150	16	2
Postage and receipt stamps				38	8	4½
Sundry expenses				34	19	2
Advertising				11	14	0
				£766	9	11½
To Balance brought down				41	4	9½
				£41	4	9½

INCOME *Cr*

	£	s.	d.	£	s.	d
By Subscriptions:						
Fellows	225	15	0			
Members	165	18	0			
Corporate members	37	16	0			
Students	4	14	6			
	434	8	6			
Less rebate to members of the Institute of Physics	11	2	7			
				423	0	11
Advertisements in *Transactions*, *less* expenses				26	8	8
Sale of publications				230	16	4
Interest				34	14	10
Physical Society—Exhibition account				10	4	5
Balance, being excess of Expenditure over Income for the year carried down				41	4	9½
				£766	9	11½
By Arrears of subscriptions received during 1927				33	12	0
Balance transferred to Accumulated Funds				7	12	9
				£41	4	9½

BALANCE SHEET AT 31st DECEMBER, 1927

LIABILITIES

	£	s.	d.	£	s.	d.
Sundry Creditors				256	13	2
Accumulated Funds:						
Balance at 31st Dec. 1926	686	18	6½			
Less Balance of Income and Expenditure account £7. 12*s*. 9½*d*.						
Less Call on Optical Convention Guarantee Fund £150. 0*s*. 0*d*..	157	12	9½			
				529	5	9
Life compositions account:						
As at 31st Dec. 1926				73	10	0
Subscriptions received in advance				4	4	0
				£863	12	11

ASSETS

	£	s.	d.	£	s.	d.
Sundry Debtors				43	10	9
Subscriptions due				16	5	6
Optical Convention Guarantee Fund:						
As at 31st Dec. 1926	200	0	0			
Less Call	150	0	0			
				50	0	0
Investment:						
£650 5% War Loan at cost				657	6	3
Cash at Bank	89	19	1			
Cash in hand	1	7	4			
Petty cash in hand	5	4	0			
				96	10	5
				£863	12	11

E. O. HENRICI,
Hon. Treasurer.

We have audited the above Balance Sheet and have obtained all the information and explanations we have required. We have verified the Bank Balance and the Investments. In our opinion such Balance Sheet is properly drawn up so as to exhibit a true and correct view of the Society's affairs according to the best of our information and the explanations given to us and as shown by the books of the Society.

KNOX, CROPPER & CO.
Chartered Accountants

Spencer House,
South Place, E.C. 2.
28*th February*, 1928.

Examined and approved on behalf of the Society.

5th March, 1928.

C. J. BECK,
R. W. CHESHIRE,
Hon. Auditors.